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PHYSICS.—*The measurement of high voltage.*[1]

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INTRODUCTION

This paper presents an outline of the basic principles used in measuring high voltages. It appraises the accuracies attained by some of the methods and devices currently in use, rather than attempts to give historical credit for discovery and invention, although numerous references are cited which should prove useful to one interested in tracing such matters. The expression "high voltage," in the title of this paper, will be construed to include voltages of the order of 100 kilovolts and higher. It will be convenient to leave out of consideration many voltage measuring devices useful in the neighborhood of 100 kv and lower but of doubtful value in extending the range to much higher voltage by increasing the proportions of the device. This demarcation also serves to exclude from this discussion the methods of measurement of voltage at extremely high frequencies because voltages of this magnitude are nonexistent at those frequencies. The first portion of this paper will logically be devoted to a discussion of certain reliable methods of extension in range from low voltage standards.

It is proper to ask why one should be interested in the accurate measurement of high voltage. One must be interested because many phenomena depend on voltage. For instance, the hardness limit of X-radiation emitted by an X-ray tube depends upon the maximum value of the voltage across the tube including the ripple or any superposed surge. Similarly the sparkover voltage of a sphere gap and the a-c flashover values for a string of line insulators depend upon the crest of the alternating voltage applied to the gap or string. In those cases it is the maximum voltage arising from the combination of all voltage components in which we are interested. In the surge-voltage breakdown test of a lightning arrester it is the crest of the applied surge that is fundamental, although the form of the surge, if it rises very rapidly, may be important. This is because with surges of increasingly steep wave front the crest breakdown voltage actually increases because it requires an appreciable though short time to establish the mechanism of breakdown. On the other hand, in the commercial sale of energy it is the effective value of the voltage and its phase with respect to the current that is important. Thus the measurement of high voltage in the cases just mentioned presupposes some knowledge not only of the magnitude of voltage, say from thousands to several millions of volts, but also a knowledge of the variation of the voltage with time. This variation of voltage with time, which may have the form of a wave, pulse, ripple, or some other shape in no way resembling our everyday conception of a wave, is called wave form.

From the foregoing discussion one may conclude that the significant characteristics of voltage to be measured, illustrated in Fig. 1, may be listed as:

1. Direct voltage (d-c voltage).
2. Effective alternating voltage (effective a-c voltage).
3. Average alternating voltage (average a-c voltage).
4. Crest or maximum voltage of a rippled d-c-, alternating-, or surge-voltage.
5. The wave form of a surge- or alternating-voltage.

[1] Address of the Retiring President of the Philosophical Society of Washington, delivered at the 1274th meeting of the Society on January 4, 1947. Received July 28, 1947.

For the measurement of voltage it has been found convenient to adopt as a primary standard, the voltage of the standard cell. The unsaturated standard cell, the voltage of which is approximately 1.0186± volts, is almost universally used as a laboratory reference standard for voltage measurements. When kept in a thermostated enclosure and used under favorable conditions, it exhibits a remarkable constancy of voltage. The small differences that may arise in a thermostated group of cells from year to year are of the order of microvolts. Unfortunately, similar electrochemical devices having 100, 1,000, or 1,000,000 times the voltage of a standard cell do not exist. Therefore, in the usual measurement of higher voltages, it has been necessary to develop devices which ultimately refer back to the standard cell.

Resistance methods of extending the range of voltage upward from the value of the voltage of the standard cell make use of the fact that by selecting suitable alloys and heat treating them properly resistors can be constructed to have a resistance, or a ratio of resistance, that remains constant to within a few parts in 100,000 over a satisfactory temperature range. The use of a potentiometer or of a tap resistor (volt box) is the simplest method for extending the range of measurements of direct voltages by reference to the standard cell. If r is the resistance from one end to the tap point and R is the total resistance including r, then the voltage e across r can be measured with reference to a standard cell by using a potentiometer and the voltage V across R is then $V = e \cdot R/r$.

Although this simple resistance method is adequate for small steady direct voltages it requires modification for the precise measurement of the high varying direct-, alternating-, surge-, and pulse-voltages that one encounters in practice. The manner in which the voltage at any instant varies with the time is a fundamental factor in the problem of measurement. It is necessary to express alternating voltage in terms of direct voltage which can be evaluated by reference to the standard cell. Instruments designed to read the same on the effective value of alternating voltage as on direct voltage are called "transfer instruments." As transfer instruments, electrostatic instruments (*1*) are favored in Great Britain,

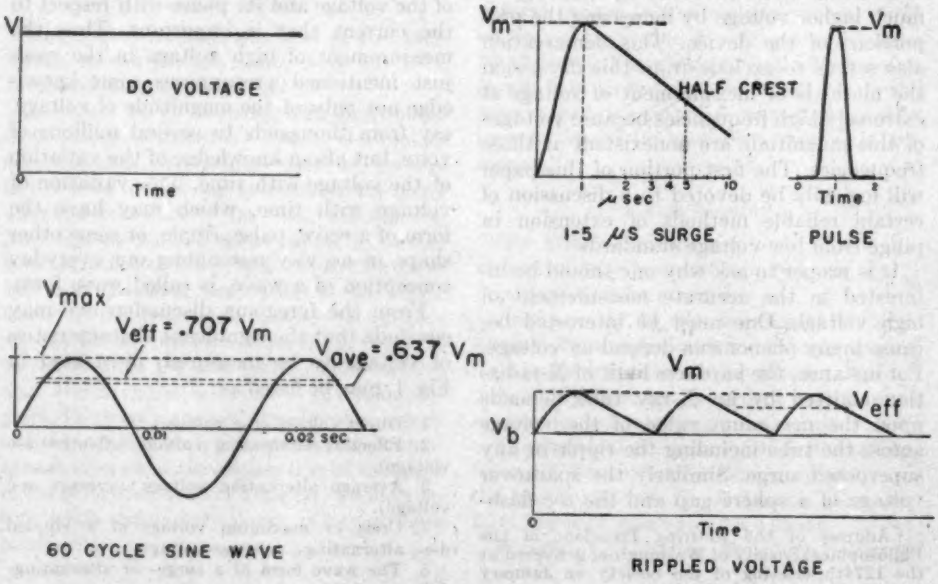


FIG. 1.—Wave forms.

while electrodynamic instruments (*2*) find favor in this country. An electrostatic voltmeter, for instance, should give the same indication for a direct voltage V as it does in the case of an alternating voltage of pure sine-wave form for which the crest or maximum voltage $V_m = \sqrt{2}\,V$.

If rectified alternating voltage is applied to a direct current voltmeter the instrument will read the average value of voltage applied to it, i.e., $V_{av} = (1/t)\int_0^t v\,dt$.

If, however, completely rectified alternating voltage is applied to a good electrostatic voltmeter the voltmeter will read the crest voltage. Crest voltage can also be determined from the length of a spark gap across which it will just cause a discharge, or it can be readily evaluated from the wave form determined by use of a calibrated oscillograph.

A more detailed knowledge of the variation of the voltage with time such as is given by an oscillograph becomes of special interest in the case of pulse and surge voltages. Thus it would seem appropriate to appraise the value of the several devices used in the delineation of wave form, and to mention each type under the particular voltage divider or device with which it is generally associated.

A consideration of high-voltage measuring devices appears to lend itself better for discussion under a classification of methods of measurement or types of devices rather than under the classification of characteristics of voltage previously outlined. The devices which are useful in measuring high voltage may be conveniently classified as to type by considering whether the method of measurement employs:

1. A high series impedance with a low-impedance instrument to indicate current through the impedance.
2. A potential divider in which a fraction of the total voltage is measured across tap points of the impedance.
3. A voltage transformer that permits measurement of a low voltage having a direct ratio to the high voltage.
4. A generating voltmeter in which a voltage proportional to the field intensity in the region of the instrument is indicated.
5. A spark discharge in which the length of the spark gives a measure of the voltage.
6. The cooling effect of an "electric wind" as in the ionic wind voltmeter.
7. Force arising from the attraction or repulsion of electrostatic charges on electrodes.
8. The deflection of a stream of charged particles by means of a known field, either electrostatic or magnetic, after their acceleration in vacuo by the voltage to be measured.

The devices used in measuring high voltage will be considered in accordance with the above classification and in the order listed.

SERIES IMPEDANCE METHOD

The simplest method of measuring high voltage would appear to be to connect a high impedance in series with a sufficiently sensitive current measuring instrument having a negligible impedance compared to the value of the high series impedance, Z. Values of the indicated current, i, would then give the high voltage, $V = iZ$. The impedance Z may, of course, be primarily resistive, inductive, or capacitive or combinations of these elements.

Series resistors.—This basically simple method has been widely used in nuclear disintegration work for direct voltage measurements, wherein the impedance Z is built of many high resistance units in series (diagram at A in Fig. 2), care being taken to insure that the current entering at the high voltage end of the resistor is the same as that leaving through the deflecting instrument at the low voltage end. For reliable measurements it is necessary to be sure that the electrical leakage across insulating supports of the resistor and from section to section is negligible and that there is negligible corona current from the units. Changes arising from self-heating must be made negligibly small or must be allowed for. The design of such a series resistor should be substantially the same as for the potential divider type to be discussed later in detail.

Series reactors.—For alternating voltage measurements, series reactors have been used as the series impedance (*3*). They have the drawback, however, of requiring iron cores at lower frequencies if the inductive reactance is to be made large in comparison with the resistance of the windings. Stray and distributed capacitance effects raise additional objections so that series reactors have been little used in high voltage measurements.

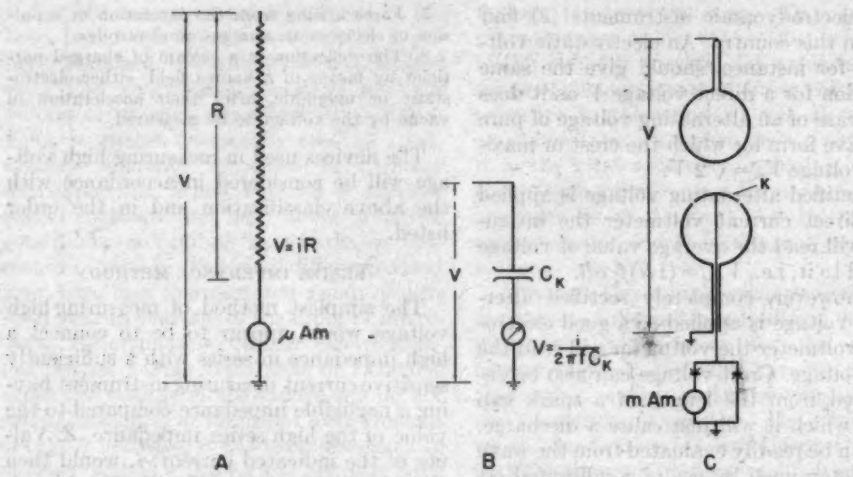


FIG. 2.—Diagrams of series impedors.

Series capacitors.—For the measurement of high alternating voltage, capacitance may be used in series with the low voltage indicating instrument, as indicated at B and C in Fig. 2. The capacitor, which must be relatively free from losses, corona, and brush discharges, magnifies the effect of harmonics present in the voltage wave form unless the low voltage instrument is of the capacitance type.[2] However, if harmonics are present, corrections can be applied. This device in a form for measuring high-crest voltage was originally described by Chubb (*4*) who employed the two spheres of a sphere gap as the capacitor, the lower and grounded sphere being insulated to permit rectification of the capacitance current to it. Such devices (*5*, *6*, *7*) appear to have been used more generally in foreign laboratories than in this country. The arrangement is indicated at C in Fig. 2. Haefely & Co. patented (*7*) such a device which employs as one electrode of the high-voltage capacitor, a large insulated circular segment of the lower sphere. The remainder of the sphere serves as the grounded guard for this segmental electrode. The upper sphere serves as the high-voltage electrode.

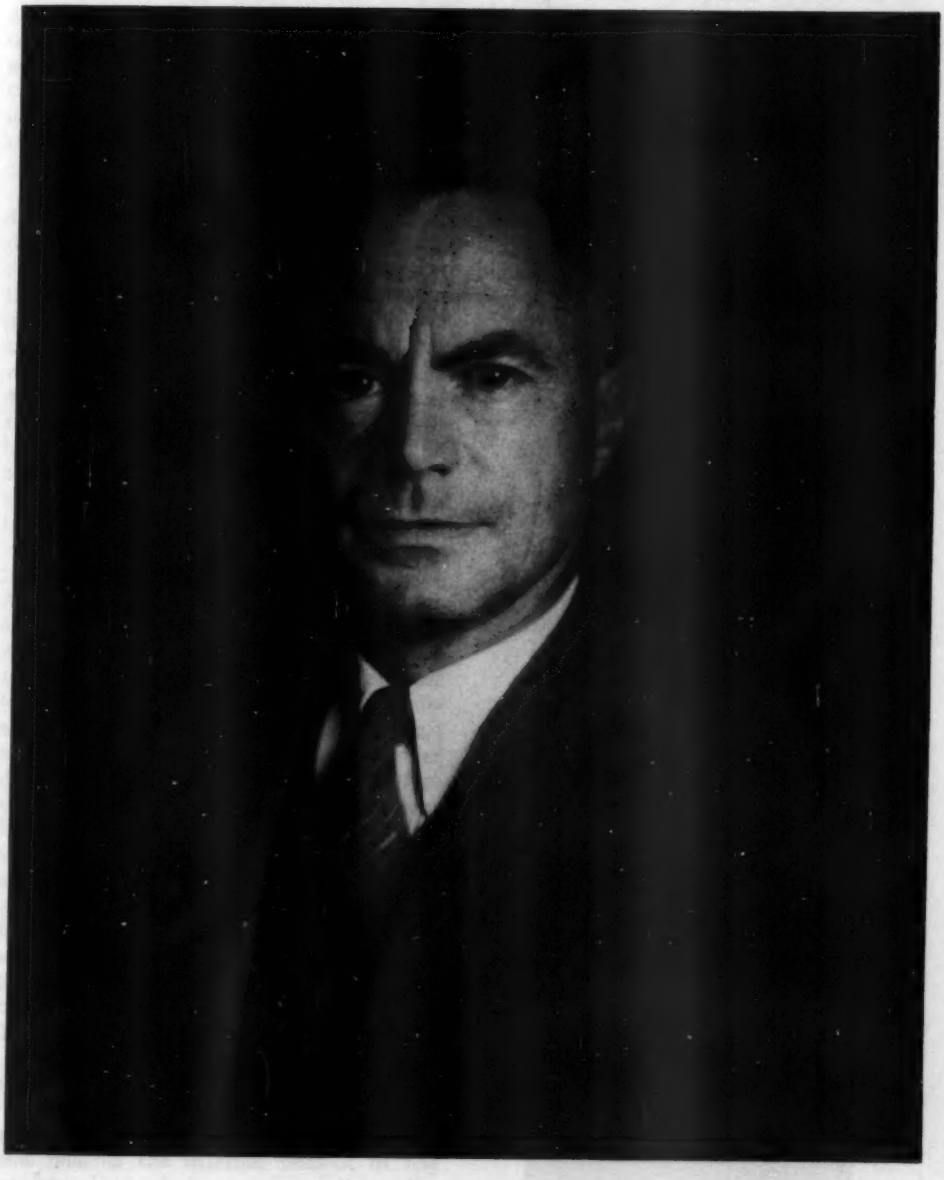
[2] Here the combination serves as a potential divider and a low voltage electrostatic voltmeter across a large capacitance gives effective values of voltage independent of wave form.

These devices generally permit only a rough computation of capacitance and therefore need to be calibrated against some other voltage standard, but they have the advantage over the sphere spark gap of giving a continuous rather than transient indication of voltage when used with an electrostatic voltmeter or rectifier-milliammeter combination. Although the early device of Chubb gave the crest value[3] of voltage, later similar arrangements (*9*) were devised that permit the determination of both crest- and effective-values of voltage, and when supplemented with a cathode ray oscillograph or synchronous commutator (*8*) give the high voltage wave form as well. For relative measurements, this series capacitance method should be good to a few tenths of one percent.

POTENTIAL DIVIDERS

The potential divider is essentially some form of impedance with one or more tap points permitting the measurement of the voltage drop between tap points by a method which preferably does not change appreciably the current flowing through the divider. The potential divider is connected across the voltage to be measured. The

[3] Except in the case of alternating voltages of unusual wave form in which there are several maxima (*8*).



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President of the Philosophical Society of Washington, 1946

value of voltage measured between taps, when multiplied by the ratio of the value of the total impedance to that of the tapped section then gives the value of voltage across the total impedance. Potential dividers are commonly constructed of sections of resistance, of resistance shunted by capacitance, or of capacitance. Types of each of these will be described.

Corona shielded resistor.—For a resistive divider one may use n resistors, each of resistance r, all exactly alike (or nearly so), connected in series, or one resistor $(n-1)$ times as large as the smaller one connected in series with it, and across which the voltage drop is measured. For use at higher voltages, both the electrical and mechanical designs of the physical device require care. Improvements in his earlier designs (*10*) have been incorporated by L. S. Taylor in a resistor, not yet described, which is in use in the measurement of the high rectified voltage supply for a 1.4-million-volt X-ray tube in the X-ray Laboratory of the National Bureau of Standards. As seen in Fig. 3, the column at the left side contains the corona-shielded resistor, which is installed immediately adjacent to the column of 10 large cascaded-rectifier tanks, each of which at maximum voltage contributes 140 kv to the total voltage of 1.4 million. This arrangement provides double shielding. The external system seen in Fig. 3 has tubular connections from the spun-metal corona shields to each section of the cascaded supply. The internal resistor assembly, also separately corona shielded, is thoroughly insulated from this outer system. Thus the currents required by the outer shields are supplied as a sectionalized direct load on the supply independently of the measuring circuit. This outer shield therefore takes care of current flow arising from external ionization, migratory dust particles, and minor surface discharges as well as surface leakage across the insulating columnar supports, and relieves the internal resistor of the resulting irregularly varying effects. In addition, the separate outer shields provide mutual field grading and the large top shield is effective in shaping the general electrostatic field. The internal resistor assembly is sectionalized, each section consisting of uniformly spaced wire-wound resistors located between toroidally shaped corona shields, which are electrically connected to the end of each group of resistors. Isolantite insulation is used for supporting the resistors and the uniformly spaced corona shields. The shields were constructed of smooth copper-tubing of circular section in order to provide satisfactory field grading along the resistor and thus to insure freedom from corona discharge currents at the highest intended operating voltage. The design provides for adequate insulation, mechanical support, and centering of this

FIG. 3.—1.4-million-volt rectifier column with shielded resistor column on left side.

column inside the outer corona shield. Each section was adjusted and thoroughly tested at rated voltage before assembly and subsequent measurements of individual sections show their resistance to be practically free from drift. These precautions were taken to make sure that the current throughout the resistor will be the same as at its low voltage end where measurement of the current is made; i.e., in order that the high voltage, V, being measured is equal to nri where nr is the total resistance of the stack of n shielded resistors. Actually the current, i, is often determined by adding a small resistor, r_s, and measuring $v = ir_s$ by means of a potentiometer.

Manganin wire-wound resistors and a relatively large current of 1 milliampere were chosen as design values in order to minimize parasitic effects of leakage, absorption, and corona currents, and thus to insure a resistor that would permit measurements to 0.1 percent or better. A current of 1 milliampere corresponds to a load of 1.4 kilowatts, so that the resistor was designed to dissipate a corresponding amount of heat. Carbon or the so-called "metallized" radio-type resistors have a much higher temperature coefficient and are in general less stable than wire-wound resistors. Considerable care must therefore be taken in their use to insure freedom from thermal and voltage effects. Although reduction in self-heating and in energy loss in such resistors may be secured by reducing the current say to 0.1 milliampere, the effects of leakage currents become relatively more important and may contribute to some extent in reducing the attainable accuracy to the order of 0.5 percent.

Still another consideration that should not be overlooked is the shunting effect on the resistance of the capacitance of the shields. In the case of a resistor of the high resistance type, sudden surges are easily transmitted through the shunting capacitances so that the measuring instrument, which must be correspondingly more sensitive, requires increased surge-protection. Thus there are drawbacks to either increasing the current in the measuring resistor to values greatly exceeding one milliampere because of increased energy loss, or decreasing it to values much below 0.05 milliampere because of the instability of the resistance insulation, and of other troubles. For much of the pioneering nuclear disintegration work (*11*) carbon resistors available in units of much higher resistance per unit length than the wire-wound type have proved both economical and useful.

It should be observed that the relatively high shunting capacitance of the corona shields of this type of resistor limits its usefulness as a resistor for alternating current measurements.

Capacitance shielded and guarded resistors for alternating current.—The resistor divider, in high favor for the measurement of direct voltage, has certain specific defects in addition to its relatively large consumption of power. It necessarily has residual inductance and stray capacitance associated with its resistance. As shown at A in Fig. 4, each section $r_1 \cdots r_n$ may be considered as having at its terminals a lumped shunting capacitance of value $C_1 \cdots C_n$, and between its upper terminal and ground a capacitance $C_a \cdots C_m$. If the value of capacitive reactance $1/2\pi fC_1$ is $\gg r_1$ and $1/2\pi fC_a \gg nr_1$ and if the impedance used in the measuring circuit shunting r_n is $\gg r_n$, the voltage division by resistance will be trustworthy. As a result of the increase in shunting effect of the stray capacitances with frequency, these inequalities grow less until the division of the applied voltage is no longer proportional to resistance.

The shielded a-c resistor (*12*) minimizes the effects of the unavoidable ground capacitances at the cost of additional energy dissipation, by employing a second or guard resistor in parallel with the first or "working" resistor. This guard resistor is so connected to the shields that it supplies current to the ground capacitances that otherwise would have to be charged through and along portions of the working resistor. In an a-c shielded resistor the working, or shielded resistor, is composed of sections of value r each contained within a metal shield or box as indicated at B in Fig. 4. Each shield is maintained at a potential corresponding to the midpoint of its enclosed resistor by connecting it to a tap point on the proper section R_n of the guard

resistor. Thus this arrangement makes the value of each shunting capacitance definite and supplies the ground capacitance current from the guard circuit. This is accomplished at the cost of a slight increase in the shunting capacitance of the individual resistors because of the capacitance to the shield in which they are located, since one end of the enclosed resistor is above and the other below the potential of the shield. However, because the potential difference across the capacitance of either end of the resistor element to its shield is only one-half the voltage drop in this section of resistance r, the shunting effect need not be excessive at low frequencies, say 25 or 60 cycles. Such a resistor, composed of about 25 shielded sections, is used in a voltage transformer testing setup for phase-angle measurements and ratio measurements to 0.01 percent at the National Bureau of Standards. This resistor is rated at 0.05 amperes in each of the two (working and guard) 500,000-ohm circuits. In this device, which at 25 kv absorbs 2.5 kw, the individual sections of the working resistor are enclosed in metal shield boxes, which are filled with oil in order to improve thermal characteristics. This resistor is arranged in tiers, each tier consisting of four working resistor boxes with corresponding sections of the guard resistor supported on a mahogany framework. Tiers are assembled one above the other by means of porcelain bus-type insulators, which serve to provide additional insulation and to permit bolting together of the resistor-supporting frameworks to form a mechanically stable assembly. Each box contains 20 flat mica cards wound unifilarly with manganin wire. It is not feasible to extend the range of a-c shielded resistors and retain the same order of accuracy (0.01 percent) by this procedure much above 30 kv because of the effects of the capacitances which shunt the guard resistances. The resulting error increases as the fourth power of the voltage.

An a-c shielded resistor of this type is also satisfactory for use as a series resistor in conjunction with an indicating voltmeter or sensitive oscillograph. It may be used equally well on direct current but would ordinarily not be used because its

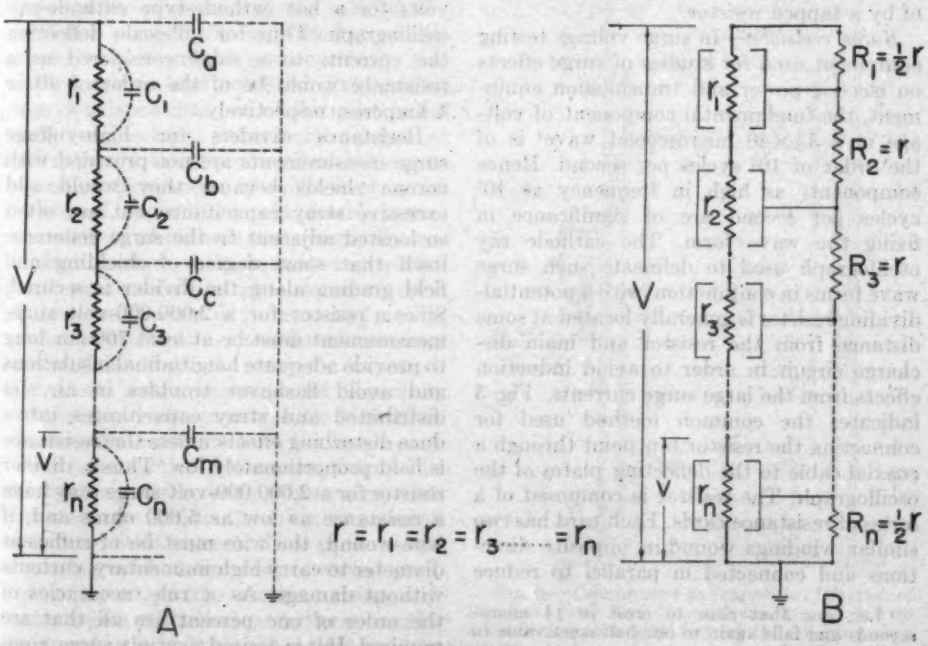

FIG. 4.—A-C shielded resistor.

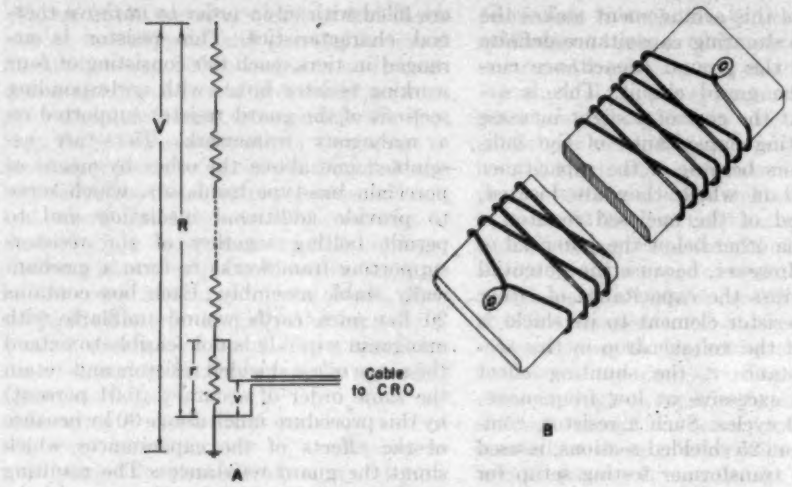

FIG. 5.—Surge resistor.

load on the source is greater than that for the simpler corona shielded resistor.

Weller (*13*) devised a shielded a-c resistor for use in transformer testing up to 132 kv in which the shield current was supplied by auto-transformers rated at 75 kva, instead of by a tapped resistor.

Surge resistors.—In surge voltage testing equipment used for studies of surge effects on electric power and transmission equipment, the fundamental component of voltage in a $1\frac{1}{2}\times40$ microsecond wave[4] is of the order of 10^5 cycles per second. Hence components as high in frequency as 10^7 cycles per second are of significance in fixing the wave form. The cathode ray oscillograph used to delineate such surge wave forms in conjunction with a potential-dividing resistor is generally located at some distance from the resistor and main discharge circuit in order to avoid induction effects from the large surge currents. Fig. 5 indicates the common method used for connecting the resistor tap point through a coaxial cable to the deflecting plates of the oscillograph. The resistor is composed of a series of resistance cards. Each card has two similar windings wound in opposite directions and connected in parallel to reduce inductance. The cable connection to the cathode ray oscillograph has a surge impedance usually of the order of 50 ohms, whereas the full-scale sensitivity of the cathode ray oscillograph is of the order of 2,000 volts for a cold cathode-type and 200 volts for a hot cathode-type cathode-ray oscillograph. Thus for full-scale deflection the currents to a cable considered as a resistance would be of the order of 40 or 4 amperes, respectively.

Resistance dividers for high-voltage surge measurements are not provided with corona shields because they would add excessive stray capacitance but are often so located adjacent to the surge generator itself that some degree of shielding and field grading along the divider is secured. Since a resistor for a 2,000,000-volt surge measurement must be at least 700 cm. long to provide adequate longitudinal insulations and avoid flashover troubles in air, its distributed and stray capacitances introduce disturbing effects unless the resistance is held proportionately low. Thus a divider resistor for a 2,000,000-volt surge may have a resistance as low as 5,000 ohms and, if wire-wound, the wire must be of sufficient diameter to carry high momentary currents without damage. As a rule, accuracies of the order of one percent are all that are required. If it is desired to study surge com-

[4] I.e., one that rises to crest in $1\frac{1}{2}$ microseconds and falls again to one-half crest value in 40 microseconds.

ponents of the order of 10^8 or 10^9 cycles per second the residual inductance of each element and the distributed and particularly the non-uniform stray capacitance effects, assume especial significance in surge resistor dividers. For those frequencies, supplementary capacitance elements (*14*) may be added to the resistance elements of the divider in such a manner as to make uniform the capacitance shunting effect on each element and thus insure proper division of the surge voltage and its correct delineation by the oscillograph. The present interest in better voltage measurements of surge wavefronts of duration less than one microsecond should lead to improved designs of surge-voltage resistor dividers.

The cathode ray oscillograph plays such an important role in the field of surge-voltage (and surge-current) measurements that its contribution should be mentioned at this point. Although its value for use at lower frequencies should not be underestimated, it stands alone in versatility for use in high-frequency, surge, and pulse measurements. It owes this versatility to the small inertia of its electron beam, which serves at the same time as the moving element and pointer. The cathode-ray oscillograph, with a suitable sweep circuit, amplifiers, shunts, and potential dividers, has been developed into one of the most useful pieces of electrical laboratory equipment and covers a range from a few cycles per second to frequencies of millions of cycles per second. Developments in electron optics and of new phosphors are constantly enlarging the place of the cathode-ray oscillograph as a useful precision device in spite of the complication of its accessory equipment. In the future an order of accuracy better than 1 percent may be expected. For most measurements, and especially those of high voltage surges, its high effective impedance results from the low capacitance between its deflection plates. The energy loss, arising largely from stray ions and electrons within the tube, is so small as to be of little concern. Thus in the visual or photographic delineation of wave, surge, and pulse shape the starting point now seems to be a calibrated cathode-ray oscillograph except in very special instances in the low frequency range where a higher order of accuracy is required.

Capacitor dividers.—Because residual inductance and residual capacitance effects in a resistance divider are unavoidable, not only in the resistance elements themselves but also in their electrical connections, it is natural to turn to the use of capacitance elements for alternating voltage division. The capacitance divider generally consists of a single high-voltage guarded-electrode capacitor in series with a low-voltage capacitor of very much higher capacitance. The

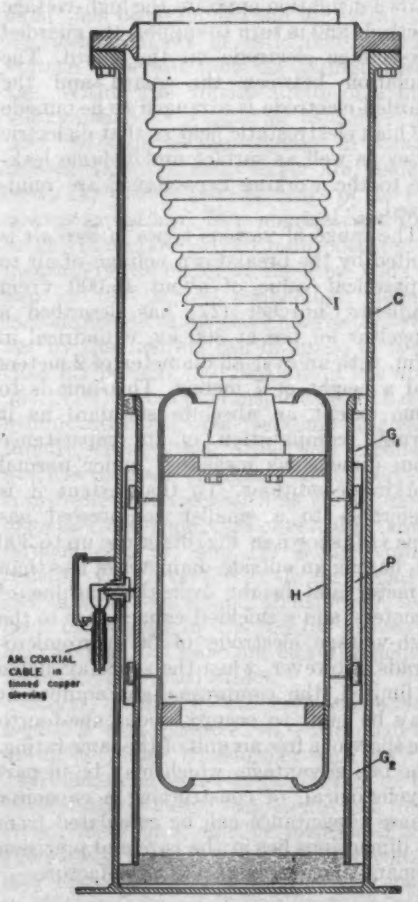

FIG. 6.—Compressed-gas capacitor. Diagram of Bousman and Ten Broeck capacitor altered to include complete shielding of the working electrode.

residual inductance effects in capacitors are minimized by properly shaping their sizable conducting parts. The residual resistance effects are minimized (1) by using high grade solid insulation for the electrode supports in order to keep electrical leakage through and across the surface of the insulation low; (2) by using free-air or compressed gases (*15*, *16*) as the dielectric because of their low dielectric loss; and (3) by using electrodes with well-rounded contours and smooth surfaces to insure freedom from corona discharge. It is customary to support the guard electrode on its own insulation opposite the high-voltage electrode and in turn to support the guarded low-voltage electrode on the guard. The insulation between the guard and the guarded electrode is arranged to lie outside the high electrostatic field so that dielectric losses as well as surface and volume leakage to the working capacitance are minimized.

The range of various types in free air is limited by the breakdown voltage of air to a practical value of about 15,000 v/cm gradient. Churcher (*17*) has described a capacitor for use at 300 kv, cylindrical in form, with an over-all diameter of 2 meters and a height of 7 meters. This unit is to some extent an absolute standard as it permits computation of its capacitance from dimensions measured under normal working conditions. To that extent it is preferable to a smaller compressed gas type (*16*) shown in Fig. 6[5] for use up to 300 kv, having an outside diameter of less than 1 meter and height over the bushing of 3 meters, and a shielded capacitance to the high-voltage electrode of 50 micromicrofarads. However, when the space available is limited, the compressed-gas equipment may be built to occupy about one-fourth the space of a free air unit of the same rating. The one advantage, which may be in part psychological, of constructing a capacitor whose capacitance can be calculated from its dimensions lies in the care and precision demanded in its design and manufacture.

[5] In this figure the original design of Bousman and Ten Broeck has been modified to show complete shielding of the outer guarded cylindrical section by the guard.

A rather recent and desirable circuit arrangement using a compressed-gas shielded capacitor for testing potential transformers is described by Bousman and Ten Broeck (*16*). Their circuit arrangement is similar to a Schering bridge, i.e., a bridge in which the A and X arms are capacitances instead of resistances. The difference lies primarily in the mode of supplying the voltage to the bridge, the high-voltage arm (A) being supplied by connection to the ungrounded end of the high-voltage winding of the transformer, and the low-voltage arm (X) being connected to the ungrounded end of the low-voltage winding. Thus if this bridge is balanced when supplying power to one winding of the transformer, one may determine from the settings of the bridge arms both the voltage ratio and phase angle of the transformer. A simple reconnection of the bridge arms to a suitable supply permits quickly checking the constancy of the bridge arm components before and after ratio and phase angle measurements. Thus in this bridge reliance for the ratio measurement is placed primarily not on capacitances but on the constancy of resistance coils which are more suitable as reference standards because of their stability, while the phase angles are based on the air capacitors. An extension in range to higher voltages might logically follow the arrangement of Bousman and Ten Broeck without serious reduction in the accuracy of 0.1 percent claimed for their equipment.

The subject of high-voltage wave form should also be considered in connection with capacitance dividers. Offhand, capacitance dividers would appear to be ideal for use with the cathode-ray oscillograph, as its impedance is essentially capacitive reactance. In surge measurements, however, it is usually both desirable and convenient to locate the cathode-ray oscillograph at some distance from the surge circuit in order to minimize inductive effects. This involves the use of a fairly long high-quality cable (preferably coaxial) connecting the divider to the oscillograph so that the surge impedance of the cable, primarily resistive, rather than the capacitive impedance of the oscillograph plates assumes the major role in the measurement

circuit. Thus, as suggested earlier, a surge resistor is to be preferred although surge capacitor dividers (*18*) have been used. For lower-frequency measurements this objection does not exist to the same extent and capacitor dividers with cathode-ray oscillographs as well as with amplifiers supplying electromagnetic oscillographs (string or loop in use up to several thousand cycles per second) have been found useful in delineating wave form with an accuracy of a few percent.

A capacitance-divider method yielding a high order of precision in delineating low-frequency wave form is due to Silsbee (*19*) who, in line with the early work of Rosa, used a point-by-point method. In his device a potentiometric balance by means of a quadrant electrometer is obtained across the low voltage portion of a capacitance potential divider for as many points in a repeated voltage wave as may be desired, thus permitting the evaluation of crest-, average-, and effective-values of the wave form. This method requires a synchronously driven contactor which may be set accurately for each balance point selected for delineating the wave. The accuracy of measurement is very high and appears to be limited primarily by the steadiness of the alternating voltage source, say to a few parts in ten thousand.

TRANSFORMER METHODS

Voltage transformer.—The method of measuring high alternating voltage in common use in the United States employs a step-down transformer termed a voltage or "potential" transformer by the manufacturer in order to designate its intended use in voltage and power measurement. The high-voltage winding is connected across the terminals of the voltage source to be measured, a voltmeter is connected across the low-voltage winding and its reading is multiplied by the ratio of transformation to obtain the value of the high voltage. The ratio of voltage of the high-voltage winding to that of the low-voltage winding of a well-designed transformer remains nearly constant over a wide range of voltage. The measured values of ratio of well-built transformers kept under normal laboratory conditions have been found to remain remarkably constant over long periods of time, variations in ratio requiring for their detection measurements having an accuracy of the order of 0.01 percent. Departures from nominal ratio have been determined by resistance bridge methods (*20*) up to 30 kv with a precision of 0.01 percent and by capacitance bridge methods up to 132 kv with a precision of 0.1 percent or better (*16*).

Where symmetrical multiple high-voltage windings are provided in a voltage transformer the following "series-parallel principle" has been found valid for extrapolating measurements of ratio factor at low voltage to permit their use at higher voltage. Within the voltage limits of a high-voltage shielded resistor or capacitor, and with the high-voltage windings in parallel, measurements of ratio factor are made to cover the voltage per coil range of the low-voltage winding. The nominal ratio for series connection is then multiplied by the measured ratio factor at the same volts per coil for the parallel connection. Reliable measurements of effective alternating voltage by this method can be made to better than 0.1 percent (*20*) and are in use up to 250 kv. The cost of transformers with such symmetrical multiple windings increases rapidly with voltage. Other less expensive and less accurate (1 percent to 0.5 percent) transforming devices such as (1) a number of small chain-connected or cascaded transformers (*21*, *22*) and (2) a high-voltage resistor (*23*), reactor (*24*), or capacitor (*25*) in series with a small transformer, have been introduced in Europe for measuring high voltage but have not met with general favor in the United States.

Supply transformer with high-voltage winding tap or with voltmeter coil.—Although the use of a voltage transformer with only an instrument connected as the burden on the low-voltage winding represents the ideal arrangement, it should be mentioned that adequately precise values of high voltage may often be deduced from voltage measurements made on the low-voltage input windings. This is particularly true if the resistance and leakage reactance of the high-voltage winding are low and the cur-

rent drawn by the load on the high-voltage winding is small. Better still, an instrument connected between ground and a tap point on the high-voltage winding (*26*) near its grounded end may serve for measuring a relatively low voltage which will be proportional to the high voltage except in so far as the voltage across the tapped section of winding is affected by distributed and stray capacitance currents which flow through it from the rest of the high-voltage winding. Fig. 7 shows three such 350 kv 60 c/s 1,000 kva transformers in the High Voltage Laboratory of the National Bureau of Standards. These units are shown connected in cascade to give 1,000,000 volts. Each unit has a high-voltage winding tap connection giving an accuracy of voltage measurement of about 2 percent at full load and correspondingly better accuracy at lighter loads. Still another arrangement consists in providing a third winding or voltmeter coil (*27*) so located relative to the low- and high-voltage windings that the magnetic flux linked by it automatically takes into account any voltage drop in the high voltage winding arising from the load connected to it. An accuracy of one-half of 1 percent at full-load leading current and better accuracy at smaller loads is claimed for a good design. These latter arrangements are not considered to be as trustworthy as the use of a separate voltage transformer.

FIG. 7.—Three transformers connected in cascade to give 1,000,000 volts.

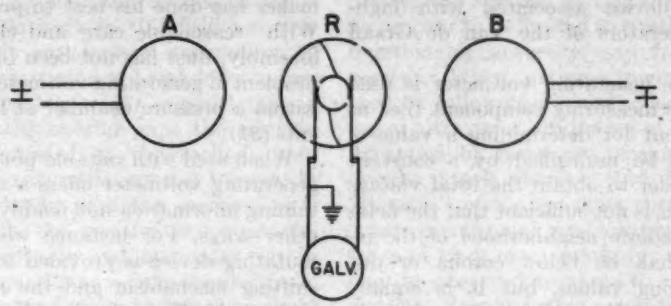

FIG. 8.—Bipolar generating voltmeter.

GENERATING VOLTMETER

The generating (rotary) voltmeter (*28*) first described by Kirkpatrick has been useful in estimating local potential gradients and as an auxiliary control device. It has been likened to a d-c generator, but instead of currents induced by moving wires in a magnetic field it employs a configuration of electrodes which permits the commutation of charges induced on plates alternately exposed to and shielded from an electrostatic field. Fig. 8 shows the diagram of a bipolar generating voltmeter. Fig. 9 shows a ceiling-mounted type designed by Behr that employs a sector disk as the rotating element.

The fundamental idea has been incorporated in many designs. Because of the necessity of alternately exposing and shielding the active plates (electrodes) the generating voltmeter appears to offer greater promise for use in relative measurements than in absolute measurements. Thus it is usually first calibrated in terms of other satisfactory low-voltage standards, prior to use at higher voltage, but it may be used in those cases not requiring a high order of accuracy and thus amenable to simplifying assumptions for the purpose of computing the high voltage from dimensions. By so shaping the high voltage electrodes that discharges and consequent space charges are avoided it may be used by extrapolation techniques to extremely high voltages both on direct and alternating voltage. Without an incorporated high-voltage electrode it is essentially a gradient measuring device. It has been useful in a study of atmospheric electric charge and field phenomena responsible for lightning (*29*), and as a voltage

FIG. 9.—Rotating segments of Behr generating voltmeter.

measuring device associated with high-voltage generators of the Van de Graaff type.

When the generating voltmeter is used as a voltage measuring component (i.e., as an instrument for determining a value of gradient to be multiplied by a constant factor in order to obtain the total voltage difference) it is not sufficient that the fields in the immediate neighborhood of the instrument shall be below corona or discharge-forming values, but it is equally necessary that the gradients at surfaces in the neighborhood of the sample field as well as those at the high-voltage electrode be below discharge-forming values and that there be no nearby relatively large sources of air ionization or dust. The effect of dust and charged particles may indirectly produce serious distortions in high fields by being deposited and aligned on otherwise smooth polished metal surfaces so as to form the necessary points for initiating discharges and consequent space charges that would otherwise not exist. If the charge on the surface of the segments alternately exposed to the electric field is to be in definite ratio to the total field, then at no place in the field may the gradient exceed the approximate breakdown gradient, 30 kv crest/cm, in air at NPT. The practical limit is actually much lower. For instance, the value of average gradient at which self-propagating discharges occur in the case of thunderstorms appears to be about 10 kv/cm. In the case of the Brooks electrometer (*30*) discharges have been known to occur between the parallel faces of the electrometer plates when the voltage applied divided by the spacing had a value of 5 kv eff/cm. Thus in air at NPT it is doubtful that for a generating voltmeter an average value of gradient exceeding 7 kv max/cm with an upper limit of 20 kv/cm at the electrode surfaces can be employed continuously without some error in measurement arising from the above causes. Presumably this practical limit arises from the almost ever-present small particles of dust (insulating or semi-conducting) which when deposited on the surface upset the ideal condition of pointless smooth surfaces one wishes to assume after the instrument maker has done his best to produce them. With reasonable care and cleanliness in assembly, dust has not been found to be a problem in generating voltmeters operating within a pressure chamber at higher gradients (*31*).

When used with suitable precautions, the generating voltmeter offers a means of obtaining information not readily available in other ways. For instance when its commutating device is provided with a phase-shifting mechanism and the rotor is synchronously driven it provides a means of determining wave form (*32*) at high voltage with practically no load on the source being investigated. It is effective on a rippled direct voltage as well as on alternating voltage. When used for determining wave form it may be located in an undisturbed and readily accessible portion of the high voltage field. The generating voltmeter method of determining wave form should be good to a few tenths of 1 percent.

AIR SPARK-GAP BREAKDOWN

Sphere and rod gaps.—If an accuracy of the order of 3 percent in determining crest voltage is sufficient, as in the case of insulator testing, the sphere spark gap in air is useful as a crest voltage measuring device. For voltages above 17 kv spheres of 6.25 cm diameter and larger (up to 2 meter diameter for approximately 2,000,000 volts) operated under controlled conditions serve as voltage standards for electrical breakdown measurements of dielectrics (*33*). Earlier theories of breakdown of sphere gaps assumed that pure air, as well as other gases, has a definite breakdown strength or breakdown gradient at normal pressure and temperature. Paschen's law relating the length of the breakdown gap with air density permits correction for usual temperature and pressure variations. Russel, Dean, Peek, and others have given empirical relationships based in part on electrostatic field theory for both sphere and cylindrical gaps, which, although they fit well in a limited domain of pressure and temperature, are not so satisfying as relations (*34*) developed at a later date on the basis of the newer atom-physical background. The detailed work on discharges in gases by Loeb

(*35*) and his collaborators as well as much other valuable work in this field has provided a fairly satisfactory explanation of some of the scattering of breakdown values of spark gaps. Meek (*36*) suggests that in the case of the shorter gaps the electron avalanche initiated at the cathode constitutes the usual initial process whereas in the case of larger gaps the mechanism is more akin to the positive streamer discharge of lightning and originates within the gap at some distance from the electrode. For gaps of intermediate length there lies a domain in which the initiation may be of either variety and such gaps show a larger scattering of breakdown values. The probability of a free electron existing in the right location to initiate a discharge is, of course, an important factor in the scattering of the initial breakdown voltage when the time of application of voltage is extremely short. Irradiation (*37*) of small electrodes of the gap with radium or with ultraviolet light to produce photoelectrons is helpful in reducing this type of scattering but appears not to be necessary in the case of large spheres because of the much higher probability, in the larger volume of air between the spheres of the presence of an initiating ion or electron.

An idea of the effectiveness of ultraviolet irradiation in reducing scattering may be cited in the case of 12.5 cm diameter brass spheres. Irradiation of the spheres by an open carbon arc reduced the scattering of individual 60-cycle sparkover values by a factor of 5 as compared with the results obtained without irradiation. On the other hand the average values of sparkover voltage were lower by from two to five percent in the irradiated case, the amount of lowering being dependent on the intensity of radiation.

Basing his work on the detailed information now available on the mechanism of spark formation Ver Planck (*38*) appears to have successfully correlated the enormous amount of data on sphere spark gaps.

From the very nature of the spark between spheres and of corona on cylinders, voltage measurements based on sphere gaps and corona cylinders (*34*), because of their dependence on surface shape, cleanliness of the surface, and cleanliness of the air, appear to be limited to a rather low and questionable accuracy, say from 1 to 3 percent. When extreme precautions are used by following a ritual of cleansing, the use of ultraviolet irradiation of the spheres, limitation by resistance of surface pitting by the spark current, and by insuring "cleanup" of the sparking surfaces of the sphere gap through preliminary sparking, a series of 10 or more sparkover values often may be observed to agree to within ± 0.1 percent. However, this apparent high precision, equal to that of the high-grade indicating voltmeter employed as part of the equipment in making such observations, is deceptive. Painstaking observations made the following day under seemingly identical conditions may agree among themselves to the same precision but their average value will almost invariably differ by several tenths of one percent, and sometimes by more than 1 percent from those made on the previous day. In spite of its low order of accuracy the sphere gap serves as a commercial standard (*33*) for high alternating- and surge-voltage measurements apparently because of its basic simplicity. In larger sizes it gives a useful measurement of the maximum value of surge voltage and essentially serves as a voltage limiter when it is used in parallel with a device undergoing voltage-withstand tests.

Simple needle gaps, as a matter of historical interest, were once accepted as alternative standard voltage measuring gaps, but as a result of the inherently high scattering of values of sparkover voltage, variation in sparkover values with changes in humidity, and large scattering in sparkover voltage when used for measuring surge voltage, they have been discarded as standards. Rod gaps (*39*) in which the electrodes are used repeatedly as contrasted with the formerly prescribed use of new #00 needles for each sparkover of the needle gap, have sparkover values which are also affected by humidity to about the same extent as the flashover of porcelain insulation and appear to have replaced needle (or point) gaps for those uses where gaps are desired for correlating the flashover voltage of insulators.

IONIC WIND VOLTMETER

The Ionic Wind Voltmeter described by Thornton, Waters, and Thompson (*40*) merits some mention because it represents a unique application of a thermal method to the measurement of high alternating voltage. Use is made of the cooling effect on a heated filament arising from "electric wind." (See Fig. 10.) The heated filament, with a suitable grounded shield, is located at a distance from the high-voltage electrode in such a position that, although in the electric field, it will always be below corona-forming voltage. Ions that may be present move back and forth as a result of the alternating electric field and in striking neutral molecules increase the general molecular motion. This results in an increase in cooling effect on the heated filament proportional to the electric field. A filament that has a high temperature coefficient of resistance is connected in one arm of a Wheatstone bridge. The bridge out-of-balance indicator is then calibrated in terms of the high voltage applied to the Ionic Wind Voltmeter. Although this device may be constructed to have good sensitivity and is useful as a control device or relay, its indications are affected by change in wave form and an accuracy of only ± 2 percent is claimed for it.

ELECTROSTATIC VOLTMETERS AND ELECTROMETERS

Electrostatic voltmeters and electrometers basically depend for their indication on a measurement of the force of attraction between charges on the movable portion of one electrode surface and charges of opposite sign on another fixed electrode surface. By arranging the movable portion of the electrode to be part of a suitable geometric surface—sphere, ellipsoid, or plane—it is possible to devise an instrument in which the voltage applied can be computed theoretically from measured dimensions and the measured force of attraction. An electrometer designed to approximate quite closely the theoretical assumptions as to the conductor shape and relative dimensions required for simple theoretical computations, and thus to permit computation of the value of applied voltage from dimensions and the resulting force, is termed an absolute electrometer. This is in contradistinction to the term electrostatic voltmeter, which signifies an instrument that may be used for relative measurements but that requires calibration by means of some other standard of voltage measurement. A number of designs of high-voltage electrostatic voltmeters (*41–51*) have been constructed. Such instruments require much less electrical energy for their operation than an electrodynamic instrument with a series resistor. Corners rounded sufficiently to avoid electric discharges, high-quality insulation, and electrode spacing adequate to prevent discharges are prerequisites in the construction of both electrostatic voltmeters and electrometers.

Electrostatic voltmeters.—With a few exceptions (*46, 47, 49*) the high voltage electrostatic voltmeters follow the pattern of the Kelvin (*52*) guard-ring electrometer by having a guard ring for the attracted disk or movable electrode while placing less emphasis on the flatness of the movable electrode. Provision is usually made for

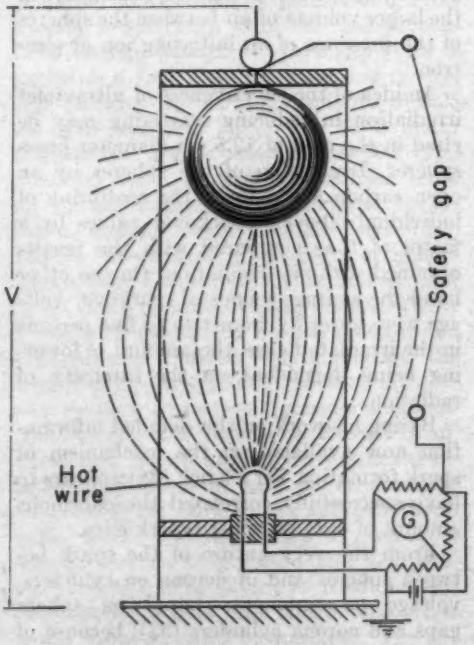

FIG. 10.—Ionic wind voltmeter.

change in range by adjusting the spacing between the high-voltage electrode and grounded electrode of which the moving element usually forms a part. It is interesting to consider the developments in these instruments over a few years as shown in Figs. 11, 12, and 13. In the early design of Abraham and Villard (*41*) (1911), Fig. 11, the curvature of the disk and guard is nearly spherical. The moving system is rather massive with a separate damping chamber within the guard. The Imhof (*44*) (1926) design, Fig. 12, provides a flattened guard ring and fits the light-weight attracted electrode into its own damping chamber. Starke and Schroeder (*43*) (1928) in one model, Fig. 13, employed a relatively larger flat-guarded electrode and a flat-strip suspension for the movable rectangular flat electrode, *P*, providing it with a mirror instead of a mechanical pointer, as well as with a balanced damping chamber arrangement. Nearby objects would be increasingly less effective in producing deflection errors at equivalent spacings in the later voltmeters. These voltmeters may be read to closer than 1 percent but unless calibrated in place, especially when used at large spacings at maximum rated voltage, are likely to be affected by nearby objects.

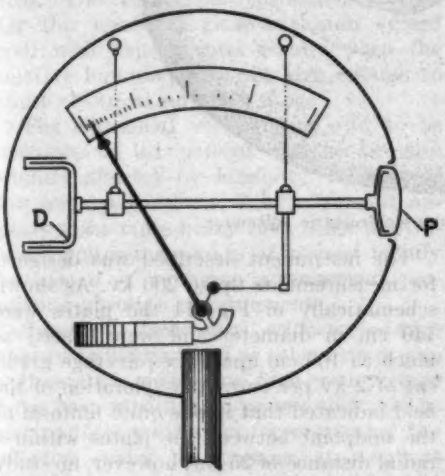

FIG. 11.—Abraham and Villard electrostatic voltmeter.

Ellipsoidal voltmeter.—The ellipsoidal voltmeter of Thornton and Thompson (*53*), illustrated in Fig. 14, is of the nature of an electrometer and satisfactory theoretical equations have been developed for it. It, like the electrometer, depends on a relatively undistorted axial field if it is to be used as an absolute instrument.

The moving element consists of a metallic ellipsoid of revolution carried on a bifilar silk suspension and is provided at its lower end with a reflecting mirror and damping

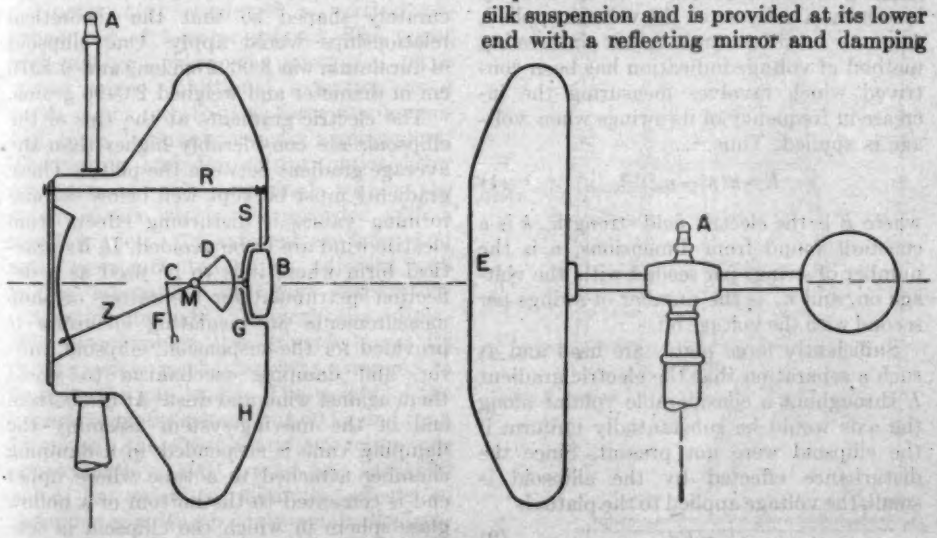

FIG. 12.—Imhof electrostatic voltmeter.

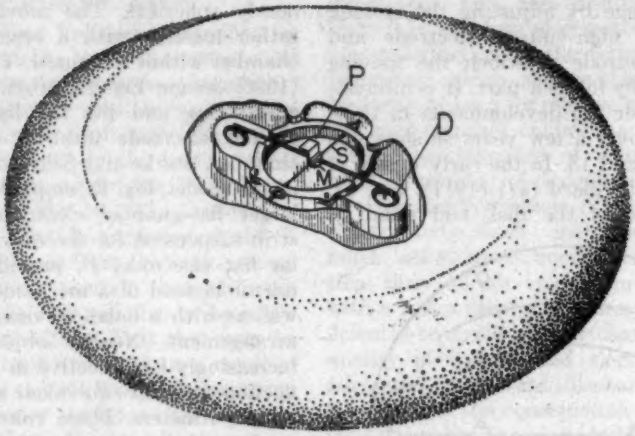

FIG. 13.—Starke and Schroeder electrostatic voltmeter.

vane. The ellipsoid is suspended with its long axis horizontal and is centrally located between two vertical circular plates facing each other and at an adjustable distance apart. Polarization of the ellipsoid by the electric field established between the plates by the source of voltage to be measured, gives rise to a mechanical couple tending to align the ellipsoid, which is initially set at an angle to the horizontal axis perpendicular to both plates. Although the change in the angular deflection of the ellipsoid may be used as a measure of the voltage applied, a more sensitive and rather interesting method of voltage indication has been contrived which involves measuring the increase in frequency of its swings when voltage is applied. Thus:

$$E = k(n^2 - n_o^2)^{1/2} \qquad (1)$$

where E is the electric field strength, k is a constant found from dimensions, n is the number of swings per second with the voltage on, and n_o is the number of swings per second with the voltage off.

Sufficiently large plates are used and at such a separation that the electric gradient E throughout a considerable volume along the axis would be substantially uniform if the ellipsoid were not present. Since the disturbance effected by the ellipsoid is small, the voltage applied to the plates is

$$V = Ed, \qquad (2)$$

where d is the plate separation.

The instrument described was designed for measurements up to 200 kv. As shown schematically in Fig. 14 the plates were 140 cm in diameter and were spaced as much as 100 cm apart (i.e., average gradient of 2 kv per cm). An exploration of the field indicated that it was quite uniform at the midpoint between the plates within a radial distance of 25 cm; however, no study of its longitudinal variation appears to have been made. Great care was taken to insure that the ellipsoids of revolution were accurately shaped so that the theoretical relationships would apply. One ellipsoid of duralumin was 3.9692 cm long and 0.5970 cm in diameter and weighed 2.0496 grams.

The electric gradients at the tips of the ellipsoids are considerably higher than the average gradient between the plates. These gradients must be kept well below corona-forming values if disturbing effects from electric wind are to be avoided. In its practical form where it is to be used as a deflection instrument for laboratory or shop measurements an insulating enclosure is provided for the suspension, ellipsoid, mirror, and damping mechanism to shield them against wind and dust. At the bottom end of the moving-system assembly the damping vane is suspended in a damping chamber attached to a tube whose upper end is cemented to the bottom of a hollow glass sphere in which the ellipsoid is centered. The upper end of the sphere is cemented to a second tube housing the bifilar

suspension and an adjustable suspension control for changing the period of swing. The control mechanism and the torsion head are mounted at the supported upper end of the tube. A spherical shape was used for the hollow glass sphere enclosure for the ellipsoid so as to permit a theoretical evaluation of the effect of the dielectric of the sphere on the electric field E at the ellipsoid. The theoretical correction derived for this spherical glass enclosure agreed well with experimental results when the relative humidity was not high enough to cause electrical surface leakage.

The ellipsoidal voltmeter is said to be accurate to 0.1 percent and to be only slightly affected by humidity. Because of low average gradient, 2 kv eff/cm, it appears to be more bulky than other electrostatic voltmeters and is of interest mainly because it is a unique arrangement permitting absolute measurements.

Sparkless sphere-gap voltmeter.—Large spheres ordinarily used as sphere spark-gap voltmeters in measuring high crest-voltage have been modified to permit their use as electrostatic voltmeters for measuring the effective value of voltage at spacings slightly in excess of sparking distances. This arrangement has been called a sparkless sphere-gap voltmeter (*47*).

Hueter (*46*) employed a vertical arrangement of 1-meter spheres. The upper high-voltage sphere was supported on a spring whose additional extension as a result of the electrostatic force was magnified by a lamp-mirror-scale arrangement. The spring and the mirror optical-lever arrangement were mounted within the sphere shank which was provided with a small window. An external arc-lamp and scale were mounted on an adjacent wall in the laboratory and gave satisfactory readings in daylight. The vertically adjustable lower sphere was grounded and its driving screw mechanism was arranged to indicate the gap length. The weight of the upper one-meter sphere was 60 kg and for a 75 cm gap the electrostatic attraction was approximately 800 grams at 1,000,000 volts. In order to minimize effects of changing gap length, only small displacements (less than 0.5 percent of the gap length) of the spring-suspended sphere were used. An oil-cup damper made the sphere motion nearly aperiodic. An accuracy of 1 percent was claimed.

Sorensen (*47*, *48*) employed a horizontal arrangement of 1-meter spheres with rather long slender shanks presumably in order to reduce effects of attraction arising from the shanks. The electrostatic attraction of the grounded sphere could be readily measured as it was supported by suspending its shank by four ropes tied to the shank at the apices of the two thus-formed V-suspensions. The upper ends of the ropes were attached to ceiling members. This laterally stable suspension possessed only a small longitudinal stability so that differences in longitudinal electrostatic forces of several hundred grams could be measured to better than one gram. A small wire in line with and attached to the end of the grounded sphere shaft ran over the rim of a bicycle wheel thus insuring low friction. A small weight pan attached to the end of the wire permitted weighing the force of attraction.

These two sphere-electrometer devices represent useful laboratory tools for they can be calibrated and used as voltmeters for measuring effective voltage. They can

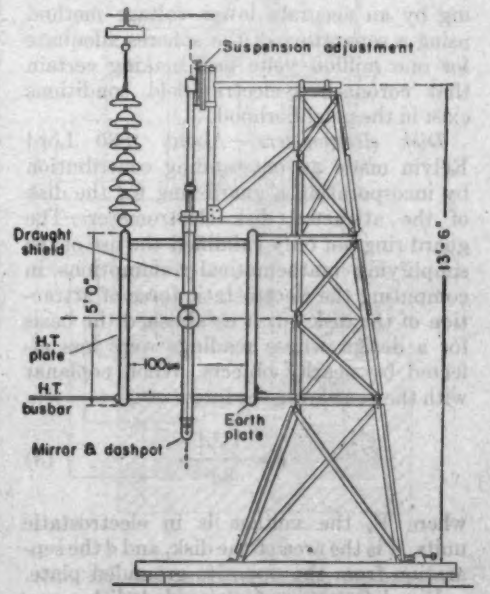

FIG. 14.—Ellipsoidal voltmeter.

also be employed in the usual manner as sphere spark-gaps for the measurement of crest voltage. If one is satisfied with the accuracy of the sphere spark-gap as a high-voltage standard, measurement of the voltage wave form permits calibration of these devices as electrometers for the measurement of effective voltage without recourse to other methods. To a very limited extent they may be considered to be absolute electrometers, particularly if adequate relative clearances to the floor, walls, leads and other conductors and insulators are maintained so that approximate corrections can be made for the presence of these objects. Simple theoretical calculations of the force of attraction can be made by the method of image charges in the case of two insulated or one grounded and one insulated sphere. For a 25-cm spacing of his 1-meter spheres Sorensen considered that no correction was necessary, and at 35 cm the effect of shanks and other nearby objects was said not to exceed 1.5 percent.

One may hope for an accuracy approaching 0.5 percent with the design of Hueter in making relative measurements up to one million volts. This would involve ample clearance for the spheres and first calibrating by an accurate lower voltage method using a separation of the spheres adequate for one million volts and making certain that corona-free electric field conditions exist in the neighborhood.

Disk electrometers.—About 1880 Lord Kelvin made an outstanding contribution by incorporating a guard ring for the disk of the attracted disk electrometer. The guard ring not only validified the use of the simplifying mathematical assumptions in computing the electrostatic force of attraction of the disk but it established the basis for a design whose readings were less effected by nearby objects. When coplanar with the guard ring the force

$$F = \frac{V_e^2 A}{8d^2}, \qquad (3)$$

where V_e the voltage is in electrostatic units, A is the area of the disk, and d the separation from the opposite grounded plate.

For deflections of a guarded disk away from coplanarity, Snow (*54*) has developed a mathematical solution which takes into account the change in force arising from change in position of the disk. This change in force might at first appear only to vary inversely with the separation d (shown by a simple differentiation of equation (3)). However, Snow has evaluated the additional change in force arising from the redistribution of the charges, which in the case of a protruding disk results in an increase in concentration of charge at the edge of the disk at the expense of the charge on the adjacent edge of the guard plate and vice versa in the case of a retracted disk. Troublesome instability in disk electrometers arising from this latter component of force has for a long time been recognized as a weakness in electrometers designed to cover a wide range of voltage measurement by adjusting the spacing d. One may either elect to provide a linear restoring force adequate for all spacings d at a considerable sacrifice in sensitivity at large spacings or provide for some adjustment of the restoring force with change in spacings at nearly constant maximum allowable gradient. The restoring force required to balance the electrostatic attraction in high voltage electrostatic voltmeters and electrometers has been provided by the following devices:

(1) Suspension of the moving electrode on one arm of a gravity balance, i.e., change of restoring force secured by adjustment of c.g. of balance relative to central knife edges (*52, 30*).

(2) Suspension of moving electrode on a coiled spring (*46, 61*).

(3) Pendulous suspension of electrode (*49*).

(4) Suspension of disk electrode assembly on a flat-strip (torsion) suspension (*43, 55*).

(5) Suspension of the disk from a metallic membrane (*50, 51*).

(6) By combining the torque provided by a flat-strip supporting suspension with that produced in a current-balance arrangement of coils which permits adjustment of the restoring force (*55*) by change in current.

The last three types merit special mention because of the novelty of their arrangement. Fig. 13 illustrates the flat-strip suspension arrangement of Starke and Schroeder. The sixth of the above arrangements, used by Nacken (*55*), employs two pairs of "current balance" coils in a con-

nection that permits adjustment of stability as well as of sensitivity. The restoring force arises in part from the vertical strip suspension which carries the disk with its plane vertical as well as the two similarly mounted astatically connected current balance coils. One pair of field coils with current i_f is connected in series aiding one moving coil and provides a torque proportional to i_f for balancing the electrostatic force on the disk; the other pair of coils with current i_m is connected in series opposing so that by reversing i_m and adjusting its value relative to the current in the moving coil the restoring force of the strip suspension toward the null or coplanar position of the disk may be either opposed or aided thus altering the stability of this system by the simple adjustment of the current in this pair of coils. Thus this arrangement permits a desirable adjustment toward higher sensitivity at large spacings of the electrodes where the deflecting force decreases.

The fifth of the above arrangements is exemplified in the devices of Rogowski and Böcker (*50*, *51*) (illustrated in Fig. 15) in which an elastic diaphragm *D* provides the restoring force for the attracted disk. The diaphragm supports an iron-cored coil (above) which is actually part of a current transformer ("Messdose") constructed with two air gaps in its iron core. The fixed coil with its core form the other part of the current transformer which is supplied from a voltage-regulated alternating-current supply. Very small changes in the air gap (moving coil position) suffice to produce full scale deflections of an ammeter connected across the moving coil and this ammeter is calibrated to read the high voltage. As part of this particular moving system, arranged for use in a compressed gas enclosure, a force coil (Druckspüle) *K* is suspended below in an iron-clad solenoid especially constructed to permit a measurement of force in terms of solenoid current. This arrangement permits, prior to assembly of the unit in the compressed gas chamber, a direct calibration with known weights on the disk for current in the solenoid against deflections of the diaphragm as indicated by the ammeter. This preliminary calibration with known weights against current is made in order to permit subsequent checking of the calibration of the electrometer by means of the current instead of weights after it has been filled with compressed gas.

Brooks absolute electrometer.—The absolute high voltage electrometer of Brooks (*30*) (Figs. 16 and 17) is illustrative of what can be accomplished in the way of precision when the attracted disk is supported on one arm of a gravity-type balance. Brooks's modification of the Kelvin electrostatic attracted disk electrometer with guard ring was designed for use in free air up to 275 kv on alternating voltage and was arranged to allow a step by step experimental evaluation of errors not readily calculable. In addition to a guard ring, it employed guard

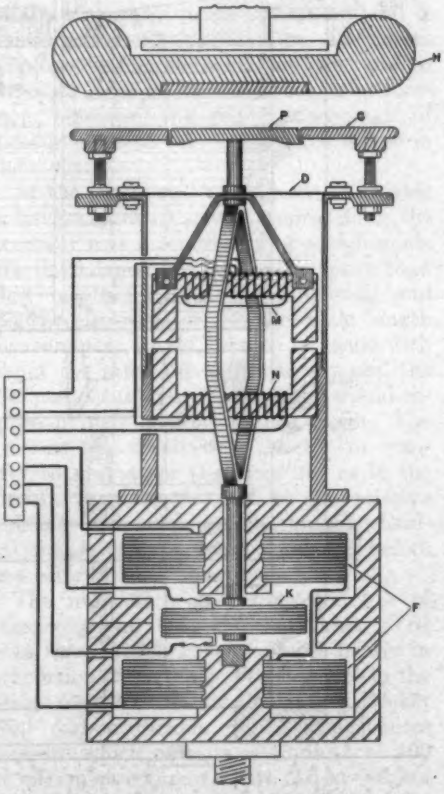

FIG. 15.—Rogowski and Böcker compressed-gas electrostatic voltmeter.

hoops equally spaced between the guarded and grounded electrodes. These guard hoops, spaced 2 cm apart, are connected to tap points on a potential dividing capacitor also across the voltage source. Thus the equally spaced hoops are maintained at equally spaced potentials corresponding to the voltage applied between the high-voltage (upper) and grounded (lower) plates of the electrometer. The hoops not only screen

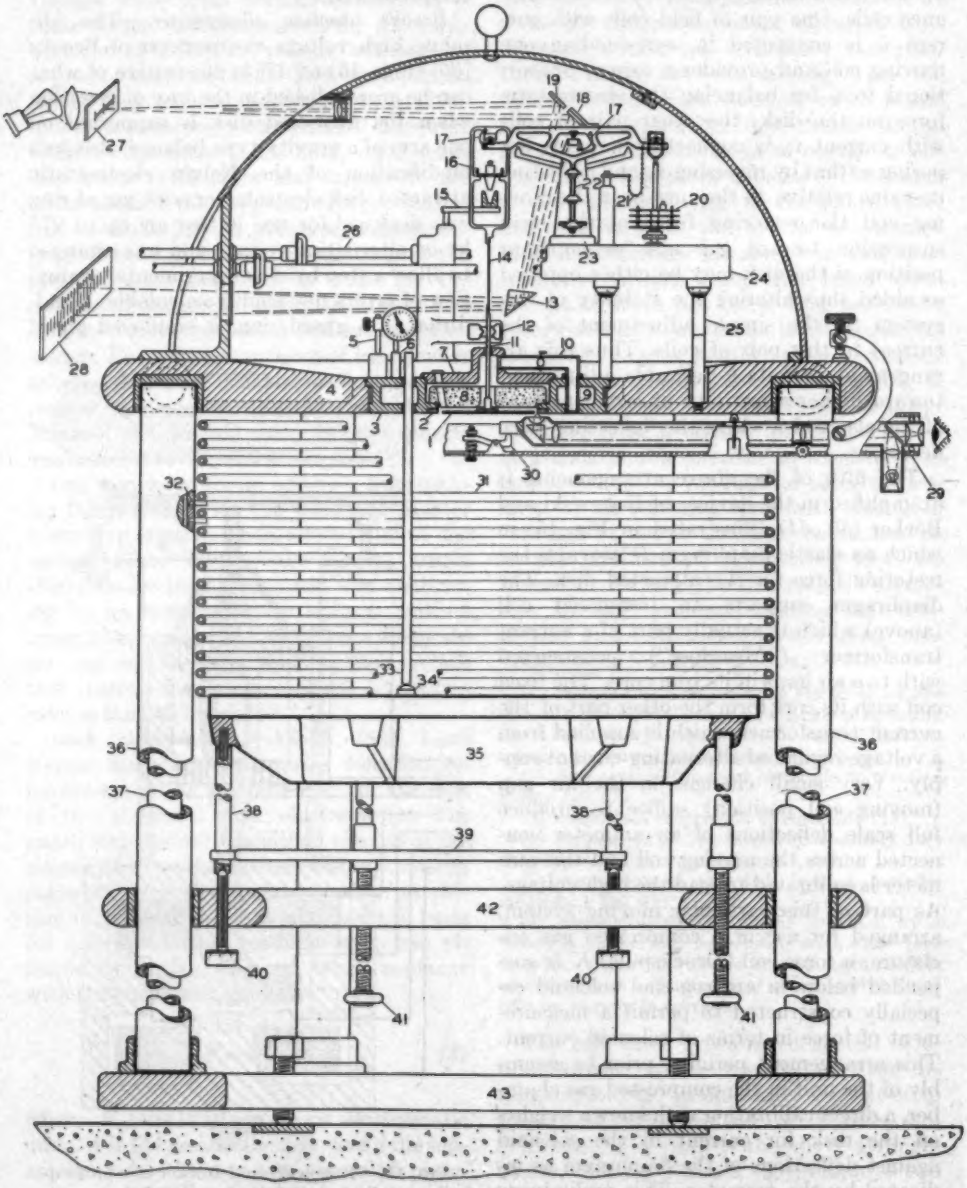

FIG. 16.—Brooks attracted disk electrometer (schematic).

the disk from external fields, but by their potential distribution tend to correct, within their diameter, electric field distortion that would otherwise arise from edge effects at the upper guard ring and lower plate. A mathematical solution of the contribution to force on the disk arising from these hoops has been carried through by Snow (*54*) and Silsbee (*30*) and has been demonstrated to be adequate by suitable experimental tests.[6] For instance by omitting hoops, or electrically shorting various sets of hoops, their potential distribution was changed drastically. For such conditions when the corresponding corrections were applied based on the mathematical solution and experimentally measured potential distribution, very good agreement in the measured values of voltages was obtained.

As a result of the work on the Brooks Absolute Electrometer, which was compared with the transformer voltmeter method of measuring voltage, it was concluded that this instrument is reliable for absolute determinations to about 0.01 percent. This work was limited to 100,000 volts—approximately one-third its rated voltage—because the clearances in the space in which the equipment was housed were inadequate. Results up to full rated value, 275 kv, are not yet available. (With the cessation of the war it is expected to extend the measurements to higher values of voltage in the modern High Voltage Laboratory of the National Bureau of Standards.)

[6] The simple equation (3) may be rearranged $V_s = 2d\sqrt{2F/A}$. This equation may be thought of as being satisfactory for measurements yielding an accuracy of 1 per cent. If an accuracy of 0.01 per cent is desired, correspondingly refined experimental techniques must be employed and additional physical measurements must be made as indicated by the larger number of terms in the complete equation for the voltage in electromagnetic units of the Brooks electrometer,

$$V_M = \frac{4v(c+h_d)\sqrt{2M_F g}}{(r_b+r_d)}\left[1+\frac{A_s-A_o}{2M_F g}+\frac{\gamma}{M_F}(S_s-S_o)-\frac{f(S_s-S_m)}{2q}+\frac{fh_m}{2}-\sum_{k=1}^{k=\infty} C_k G_k - \frac{\epsilon-1}{2}+\phi_1\left(\frac{h_d}{r_d}\right)+\phi_2\left(\frac{s}{r_b}\right)\right].$$

Compressed gas electrometer.—A consideration of the compressed gas electrometers of Tschernyscheff (*56*), Palm (*57*), Rogowski, Böcker (*50, 51*), and others who attained accuracies approaching 0.1 percent leads one to consider whether additional design features might be incorporated in the compressed gas type in order to give an accuracy approaching that of the Brooks electrometer in free air.

Actually the matter of precise weighing of the forces (less than 2.5 grams) on a 16-cm diameter disk, involved in the Brooks electrometer offers no serious problem in free air aside from the necessity of providing a carefully thermostated enclosure to avoid air currents. The possibility of having correspondingly higher forces to measure has its appeal. In the Rogowski and Böcker voltmeter the maximum force of attraction of the disk may reach 250 grams and is measured to 0.2 grams. Thus the forces employed in measurements are one hundred times as large as in the Brooks electrometer, however, the relative accuracy of measurement of this larger force is less in their device.

At the outset one would have to provide a force-measuring device approaching the accuracy and repeatability of a high-grade gravity balance, i.e., something better than that incorporated in the Rogowski and Böcker electrometer. Smaller-scale length measurement would have to be made with about the same relative accuracy and the flat metal surfaces of the plates would require a high quality optical finish. The greatest loss involved in the use of compressed gas rather than free air, as in the Brooks electrometer, lies in the relative difficulty of making and checking mechanical measurements under pressure before and after voltage observations.

The immediate gain from the use of compressed air (*15*) or other gases (*51B*) is to increase sparkover voltages nearly in proportion to pressure. For instance in the design for use to 400 kv alternating, Böcker used carbon dioxide at 15 atmospheres pressure which permits a gradient of 100 kv eff/cm as compared with 2.5 kv eff/cm in the Brooks electrometer as limited by the present potential dividing capacitor con-

nected to the hoops. Gaseous "freon" (*58*) (dichlorodifluoromethane) has between smooth electrodes about 2.3 times the breakdown strength of air at pressures up to six atmospheres where it still remains gaseous. In the case of points or sharp edges the relative breakdown strength of freon is still higher. Freon has the disadvantage of breaking down into highly corrosive products if corona or other discharges actually take place in it, making it less desirable than carbon dioxide on that account. Sulfurhexafluoride (*58C*) appears to offer some advantages over freon because of its greater chemical stability and higher equilibrium pressure at normal temperatures.

The greater size of the "free air" as compared with the "compressed gas" electrometer appears to be its chief drawback, making it too cumbersome at the highest voltages.

DEFLECTION OF FREE-MOVING CHARGED PARTICLES AND THE HIGH VOLTAGE SCALE

The cathode ray oscillograph and electrostatic (and magnetic) analyzers are examples of devices that employ the deflection of free-moving charged particles. Employing for this discussion the relations given by Hanson and Benedict (*59*), if a slowly moving stream of charged particles is accelerated in vacuo along an electrostatic field of total voltage V_a then

$$V_a e = \tfrac{1}{2} m v^2 \qquad (4)$$

where m is the mass of the particle, v its velocity, and e the charge on the particle. When a stream of particles with the velocity v is directed between parallel plates perpendicular to the electric field established by the voltage V_d between the plates then for the idealized arrangement of plates at the far edge the deflection

$$d = V_d e l^2 / 2Smv^2 \qquad (5)$$

where l is the length and S is separation of the plates. For nonrelativistic velocities if L is the distance to and D the deflection at the screen or receiver

$$D = Ld/(1/2) = V_d e L l / S m v^2 \qquad (6)$$

so that

$$V_a / V_d = Ll/2SD, \qquad (7)$$

and if the relativistic velocities are taken into account (*59*)

$$V_a / V_d \left(1 - \frac{V_a e}{2(E_o + V_a e)}\right) = Ll/2SD, \qquad (8)$$

where the rest energy $E_o = m_o c^2$ and m_o is the rest mass and c the velocity of light.

For relation (8) it may be shown that the relativistic correction is about 1 percent for electrons accelerated by a voltage V_a = 10.5 kv and increases to about 14 percent at 200 kv. The existence of a relativistic correction of such magnitudes on account of high electron velocity may be looked on as somewhat of a nuisance and as a limitation of the cathode-ray oscillograph when used for the direct measurement of high voltages. Applications of the cathode-ray oscillograph therefore seem to have been limited to the measurement of lower voltages. As is well known, the beam-accelerating voltage source for V_a is generally maintained as constant as possible in order to preserve the sharpness of the cathode spot. The voltage to be measured (or a fraction of it from the voltage divider) is applied as the voltage V_d to the deflecting plates. V_d is kept sufficiently low to leave the deflection D materially unaffected by the relativistic mass correction for velocity of the electrons.

At first thought the fundamental simplicity of this method of measuring voltage is decidedly appealing. It applies the accelerating voltage field directly to the elementary charge of the electron unhampered by additional matter. As indicated above and by equation (8) there is a disadvantage because the resulting high electron velocities even for relatively low-voltage accelerating fields become so large that relativistic corrections for moving charges must be introduced. Thus on second thought, the method involving the acceleration of electrons appears far from ideal but an examination of equation (5) indicates the advantage to be gained by using charged particles of greater mass than the electron because of the resulting lower velocity. Although what one might consider a practical

device for everyday use in the measurement of high voltage by deflecting a stream of free-moving positively charged particles has not been developed, the nuclear physicist has used such a device in his work for a number of years. To help him on his way in measuring high voltages he has established the High Voltage Scale. A short digression in explanation of how this was accomplished seems in order prior to a presentation of the contribution of the free-moving charged-particle deflection-method in this work.

The study of atom physical phenomena

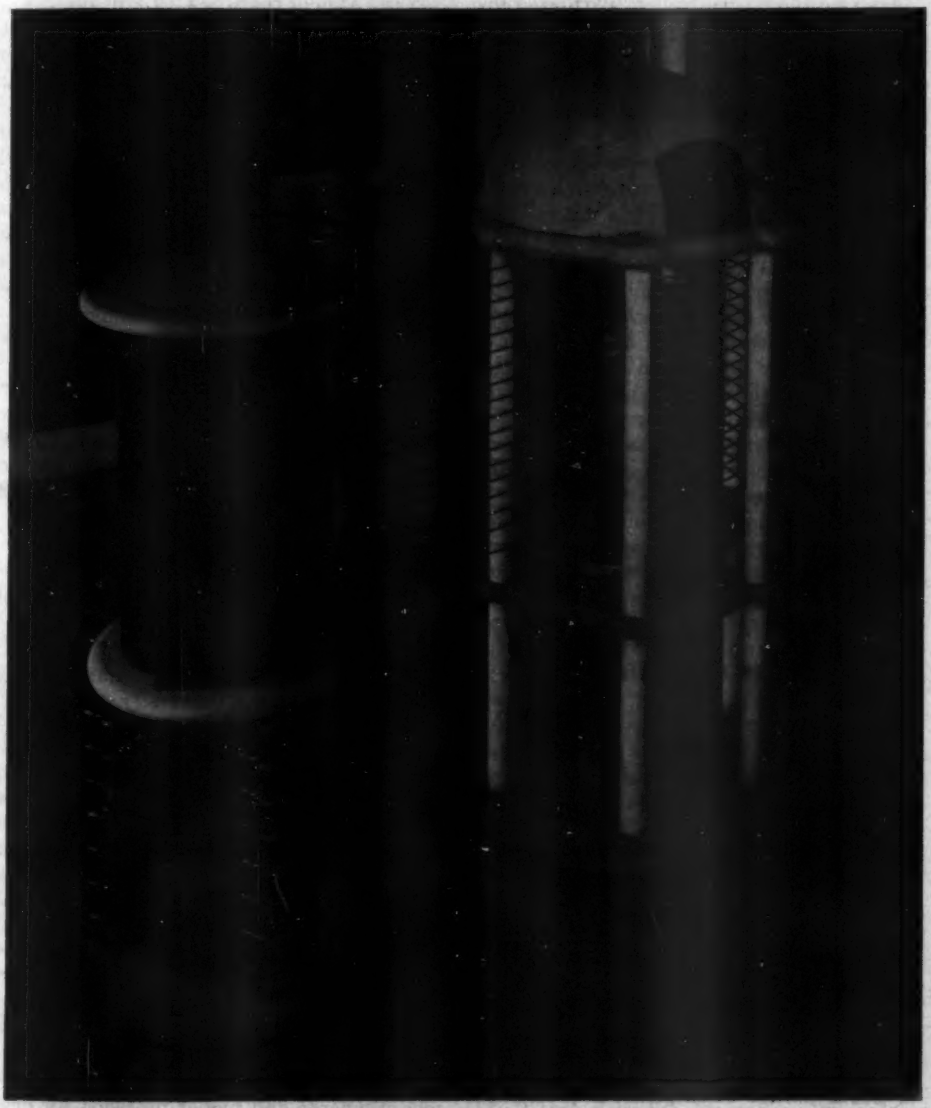

FIG. 17.—Brooks attracted disk electrometer.

led to the physicists' need for a voltage reference standard of the order of 1,000,000 times the voltage of the standard cell.

Historically, one may go back to Planck's equation $h\nu = Ve$ wherein h is Planck's constant, ν is the maximum frequency corresponding to the maximum accelerating voltage V, and e is the value of the elementary charge. Duane and Hunt (*60*) used a steady high-voltage storage battery in order to evaluate h from a careful measurement of the accelerating voltage V and the corresponding maximum frequency limit of the continuous X-ray spectrum produced. Since those measurements were made the value of h has been well established by other methods. Thus this relation affords a method of determining V by a measurement of the maximum frequency of emitted continuous X-radiation. Little use has been made of this method as a high-voltage reference standard largely because of the accuracy required in evaluating the frequency. With the advent of work on nuclear disintegration a pressing need for high voltage reference standards became apparent as the usual extrapolation methods of measuring V, the particle accelerating voltage, were both cumbersome and none too reliable. In early bombardment work it was found that resonance radiation of gamma rays occurred within a rather narrow range of the voltage used in accelerating the protons. The early careful measurements by Tuve, Hafstad, and Heydenburg (*11*) of the voltage at which these radiations occurred provided the basis for their adoption of certain values of voltage corresponding to the resonance gamma radiation for selected elements as fixed points on the High Voltage Scale.

The measurement process for establishing values for the fixed points on the High Voltage Scale consists in:

(1) Providing a source of protons which are accelerated by a carefully measured adjustable voltage V.

(2) Directing this beam of protons on a target of a selected element such as lithium or one of its salts.

(3) Measuring the gamma-ray resonance radiation effects by means of Geiger-Mueller counters or similar devices which permit a quantitative measurement of this radiation as a function of the accelerating voltage.

From plotted curves of gamma radiation against accelerating voltage (proton energy) the rather sharp maximum of gamma ray effect fixes the value of voltage chosen as the resonance voltage. By selecting elements for these reactions in which a single sharp maximum occurs and by carefully determining the corresponding voltages in terms of the standard cell, the voltages at which particular reactions occur were established as reference points on the High Voltage Scale. In a similar manner but using a boron fluoride ionization chamber (paraffin surrounding the target tube and nearby chamber) instead of the Geiger-Mueller counter, neutron counts may be made for similar reactions in which neutrons are ejected from the bombarded target by voltage accelerated protons. In this case points for the scale are determined by gradually reducing the accelerating voltage V and choosing that voltage at which there is an abrupt decrease in ionization chamber current as the limiting voltage for ejection of neutrons is reached.

Early experimental values of voltage corresponding to the resonant radiation in the bombardment of lithium by protons was fixed at 440 kv for $Li\ (p\gamma)$ with a probable error of 2 percent and a relative accuracy of 1 percent by Tuve, Hafstad, and Heydenburg (*11*) of the Carnegie Department of Terrestrial Magnetism. A redetermination of voltage values for some of the fixed points was reported in 1944 by Hanson and Benedict (*59*), of the University of Wisconsin. Their electrostatic analyzer (a device for determining the value of the electrostatic field at right angles to a beam of charged particles that will deflect the beam a given amount) was carefully constructed so that its deflection constant could be computed from dimensions as a check on values determined experimentally. Their experimental method employed an electron beam in place of the proton beam used later in their evaluation of the fixed points. The use of a low-voltage electron beam (accelerating voltages of 8 to 20 kv) and of small deflecting voltages (150 to 360 volts) permitted precise voltage measurements and higher precision for determining the deflection constant of their

analyzer than the absolute method consisting of a computation of the deflection constant using carefully measured dimensions. Various refinements including the use of a highly stabilized source for the deflecting voltage and automatic regulation of the ion-accelerating voltage reduced fluctuations and contributed to highly precise measurements of the fixed points on the High Voltage Scale. Hanson and Benedict consider the following values expressed in terms of the Million Electron Volt scale to be accurate to 0.3 percent: $Li(p\gamma)$ 0.4465, $F(p\gamma)$ 0.877, $Li(pn)$ 1.883, $Be(pn)$ 2.058. Their apparatus gave relative values agreeing to better than 0.1 percent. Their values are seen to agree within the tolerances given for the values of Tuve, Hafstad, and Heydenburg although they are approximately 1.5 percent higher.

The establishment of the High Voltage Scale based on a phenomenon unaffected by temperature, pressure, and humidity except as their abnormalities plague the collateral work of the investigator, thus represents a distinct step forward in the process of better measurements and standards for high voltages.

SUMMARY AND CONCLUSION

The principal methods in use for measuring high voltages have been outlined through the discussion of a number of devices. Mention was first made of the correlation of different methods of high-voltage measurements through extrapolation techniques in which the standard cell was used as the primary standard of voltage. Absolute high-voltage electrometers were later discussed and the good agreement between their independently determined values when compared with a standard-cell voltage-extrapolation method was noted. Concluding remarks cited the use of both the standard-cell voltage extrapolation-technique and a less precise absolute method in establishing the voltage values for certain fixed points on the High Voltage Scale.

At the moment it appears that high voltages as we know them in the laboratory stop with values of the order of 10,000,000 volts. On the other hand, charged particles come to us from space or may be accelerated in the laboratory by resonance techniques to have electron velocity equivalents approaching one hundred times that value. Presumably the future holds in store some new insulating arrangement for the collector of the high energy particles that man is able to produce—an arrangement that will permit the collector to build up to the unbelievable potentials we think of when we hear of a new machine in the rumor or blueprint stage that will produce 1,000 million electron-volt particles. Just what such voltages will be used for and how they will be measured I wish to leave as part of your field of conjecture.

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CHEMISTRY.—*Standardization of the pH scale.*[1] ROGER G. BATES and EDGAR REYNOLDS SMITH, National Bureau of Standards.

The *p*H is not a definite thermodynamic quantity, and the lack of a universally accepted definition of the *p*H scale has led to an unfortunate state of confusion. The two scales of *p*H in common use at the present time differ by 0.04 unit. Some workers are using one definition for computations and measuring a different quantity. To correct this situation it is of primary importance that a single scale be generally adopted (*1*).

Commercial *p*H meters of the glass-electrode type are now found in nearly every laboratory where chemical analyses and tests are performed. These instruments must be calibrated from time to time with buffer solutions of assigned *p*H. Two difficulties are encountered in any attempt to measure *p*H accurately. First, neither the concentration nor the activity of hydrogen ion in a buffer solution can be exactly and uniquely determined. In the second place, the potentials at the liquid junctions between the various standard and unknown solutions and the bridge solution of the reference electrode can never be perfectly matched or eliminated. Measured *p*H values will still be uncertain for this reason, even when exact standards are available. Nevertheless, the larger differences due to lack of agreement on a fundamental definition and on a method of calculation can be avoided by the co-operation of all who determine *p*H. As a means to this end, the National Bureau of Standards proposes the adoption of a standard scale of *p*H having reference points based upon certain reproducible buffers. In this discussion, the advantages and limitations of the several common *p*H scales will be considered, and the nature of the problems involved in an evaluation of the hydrogen-ion activity of the standard buffer solutions from electromotive-force measurements will be indicated.

S. P. L. Sørensen first proposed the use of the hydrogen-ion exponent (Potenz) to facilitate the designation of the extremely small concentrations of hydrogen ion of physiological significance (*2*). This unit of acidity will be called *pc*H. Its definition is formulated

$$pc\mathrm{H} \equiv -\log c_{\mathrm{H}}; \; pc\mathrm{H} \equiv -\log m_{\mathrm{H}}, \quad (1)$$

where c represents volume concentration (molarity or normality) and m is molality. The hydrogen-ion concentration, it was supposed, could be obtained experimentally by measurement of the electromotive force (emf, E) of a suitable galvanic cell. Sørensen chose the cell,

$$\mathrm{Pt;\ H_2(g),\ Solution} \left| \begin{matrix} 3.5\text{-}M \\ \mathrm{KCl} \end{matrix} \right| \left| \begin{matrix} 0.1\text{-}M \\ \mathrm{KCl} \end{matrix} \right. ,$$

$$\mathrm{Hg_2Cl_2\ (s);\ Hg}, \quad (2)$$

for the practical determination of *pc*H. The vertical lines represent liquid junctions. Ion transfer across these boundaries gives rise to an unknown liquid-junction potential, E_j, which was partially eliminated by the extrapolation procedure suggested by Bjerrum (*3*).

With the aid of standard solutions composed of hydrochloric acid with and without sodium or potassium chloride, Sørensen determined E^0, the "standard potential" or "normal potential" of cell (2). The hydrogen-ion concentration of these standard solutions was taken to be the product of the concentration of hydrochloric acid and the classical degree of dissociation derived from measurements of electrolytic conductance. By definition, E^0 is the potential of cell (2) when the hydrogen-ion concentration of the solution is 1 normal. Sørensen's value of E^0 is 0.3380 at 18° C (*2*, *4*, *5*, *6*). At 25° C, the standard potential is 0.3376 (*6*). It was intended that the *p*H at 25° C of "unknown" solutions should be computed by the simple equation,

$$p\mathrm{H} \equiv \frac{E - 0.3376}{0.0591}, \quad (3)$$

where E is corrected insofar as possible for the undesired potential at the liquid junction between the solution and 3.5-M potas-

[1] Received September 2, 1947.

sium chloride. This experimental *p*H value defined by Sørensen's value of E^0 is not, as he intended, *pc*H. It is designated *ps*H in equation (3). The constant 0.0591 in the denominator is the value of 2.303 RT/F at 25° C, where R, T, and F represent the gas constant, absolute temperature, and faraday, respectively.

In the light of modern concepts, it is clear that the laws of ideal solutions can not justifiably be employed in this way. Nor will the classical degree of dissociation yield, as Sørensen assumed, the hydrogen-ion concentration of mixtures of strong electrolytes. Activity now replaces concentration in the equations for the emf. Indeed, at a temperature of 25° C,

$$-\log \mathbf{a}_H = \frac{E - E^{0\prime} - E_j}{0.0591}, \qquad (4)$$

where **a** represents activity. The standard potential, $E^{0\prime}$, is referred to unit activity instead of normality and includes the constant chloride-ion activity in the vicinity of the calomel electrode. The activity, **a**, is the product of concentration, c or m, and an activity coefficient, f. If E_j could be evaluated, the exact hydrogen-ion activity would be forthcoming. Unfortunately, the liquid-junction potential can not be calculated without a knowledge not only of f_H and other activity coefficients but also of the compositions of the multitude of transition layers of which the boundary is composed. For this reason, the activity of a single ionic species is without physical reality (*7*).

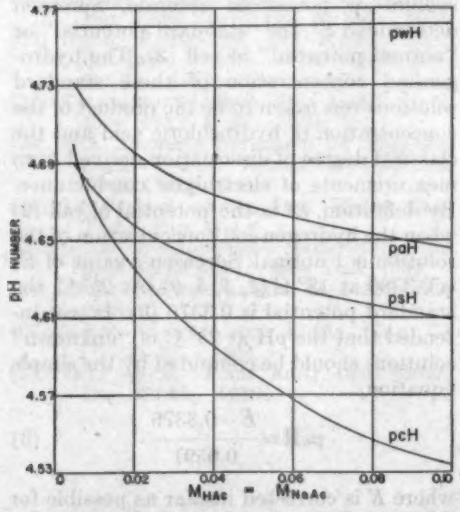

FIG. 1.—pH of acetate buffer solutions at 25° C on four different scales as a function of concentration.

The new concept of the thermodynamics of cell (2) led to the definition of *pa*H by Sørensen and Linderstrøm-Lang (*5*):

$$pa\mathrm{H} \equiv -\log \mathbf{a}_H. \qquad (5)$$

Although *pa*H can not be determined by thermodynamic methods, its character can be simply and unequivocally defined in terms of measurable mean activity coefficients. The *pa*H scale has likewise been defined in terms of the thermodynamic ionization constants of weak acids in dilute buffer solutions (*8, 9, 10, 11*).

The *p*H values, on these three scales, of buffer solutions composed of equal molarities of acetic acid and sodium acetate are compared in Fig. 1. At infinite dilution, *pa*H and *pc*H are equal, for the activity coefficient becomes unity by definition in that limit. However, the Sørensen value, *ps*H, remains lower by about 0.04 unit than *pa*H at all concentrations. The *pw*H, defined as $-\log (\mathbf{a}_H f_{Cl})$, changes but little with dilution. This unit will receive further mention. When it is desired to convert *ps*H to *pa*H, the following relationship will serve with an uncertainty probably less than 0.02 unit:

$$pa\mathrm{H} = ps\mathrm{H} + 0.04. \qquad (6)$$

The Sørensen scale, or *ps*H, is probably the scale most widely used today. The *p*H values given in the well-known monograph of Clark (*6*) correspond to this scale. Yet *ps*H is neither $-\log \mathbf{a}_H$ nor $-\log c_H$. It usually lies, in fact, between these. When a *p*H meter is standardized on this scale, all measured values must be corrected to yield a quantity that can be employed in equilibrium computations, if they are to have quantitative significance. The hydrogen-ion concentration possesses the physical reality that the activity lacks. A knowledge of the hydrogen-ion concentration would be useful, but this quantity can not readily be determined by an emf measurement with

the *p*H meter. For this reason, the activity scale has been chosen as the most practical for general use. We shall now consider the assignment of *pa*H values to the buffer solutions that will serve as fixed reference points on this scale.

Cells without liquid junction are not only somewhat more advantageous from a theoretical standpoint than are cells with liquid junction, but they are also more reproducible and can readily be measured at different temperatures. They are, however, usually impractical for routine measurements. Efforts have been made at the National Bureau of Standards to use emf measurements of cells without liquid junction to establish standards of hydrogen-ion activity with which to calibrate the *p*H meter. Each emf measurement of the hydrogen-silver chloride cell,

$$\text{Pt; } H_2\text{(g, 1 atm), Buffer solution, } Cl^-(m), \text{ AgCl(s); Ag,} \quad (7)$$

yields a value of $-\log (f_H f_{Cl} m_H)$, if the standard potential, E°, and the molality, m, of chloride ion in the solution are known, by the following equation:

$$-\log (f_H f_{Cl} m_H) = \frac{(E - E^\circ)F}{2.303RT} + \log m_{Cl}. \quad (8)$$

If the buffer solution is composed of a weak acid, HA, and its salt, where HA is either a monobasic acid or an acid anion, and *p*K for the dissociation equilibrium is known, f_r is also obtained unequivocally:

$$\log f_r \equiv \log \frac{f_{HA} f_{Cl}}{f_A}$$

$$= pK - \log \frac{m_{HA}}{m_A} + \log (f_H f_{Cl} m_H). \quad (9)$$

The quantity $-\log (f_H f_{Cl} m_H)$ will be termed *pw*H. Inasmuch as *pw*H is thermodynamically exact, its use as a unit of acidity has been suggested (*12*, *13*). The *pw*H of a buffer solution composed of a weak monobasic acid, such as acetic acid, and its salt, however, changes but slightly with relatively large variations in hydrogen-ion concentration, as shown in Fig. 1. For this reason, $-\log (f_H f_{Cl} m_H)$ is often not a useful unit of acidity in spite of the fact that it retains its significance at all ionic strengths. The *pa*H is derived from *pw*H by adding the logarithm of an ionic activity coefficient:

$$pa\text{H} = pw\text{H} + \log f_{Cl}$$

$$= pK - \log \frac{m_{HA}}{m_A} - \log f_r + \log f_{Cl}. \quad (10)$$

Thermodynamics can offer no help in estimating the activity coefficient of chloride ion in equation (10). For this reason it is usually necessary to resort to theoretical equations or to assumed relationships

TABLE 1—*pa*H OF BUFFER SOLUTIONS WITHOUT CHLORIDE AT 25° C. COMPUTED FROM THE EMF OF CELL (7)

Buffer system*	Molality of each component	Ionic strength	p_1H for— $a_i = 4$	p_1H for— $a_i = 6$	p_2H	p_4H	p_1H	p_sH	*pa*H, cells with liquid junction
Acetic acid + sodium acetate	0.01	0.01	4.714	4.717	4.716	—	—	—	4.700; 4.714
	0.1	0.1	4.648	4.663	4.663	—	—	—	4.640; 4.645
Acid potassium phthalate	0.05	0.053	4.002	4.011	4.010	—	—	4.005	4.000; 4.010
Acid potassium phthalate + dipotassium phthalate	0.01	0.04	5.169	5.177	5.174	5.170	5.164	5.168	
	0.02	0.08	5.098	5.111	5.109	5.100	5.089	5.096	
	0.05	0.2	4.991	5.013	5.019	4.996	4.969	4.987	
	0.1	0.4	4.907	4.940	4.960	4.919	4.887	4.902	
Potassium dihydrogen phosphate + disodium hydrogen phosphate	0.005	0.02	7.017	7.022	7.020	7.018	7.019	7.018	7.026
	0.01	0.04	6.956	6.964	6.961	6.958	6.961	6.959	6.963
	0.025	0.1	6.856	6.871	6.873	6.858	6.865	6.860	6.858
	0.05	0.2	6.767	6.789	6.796	6.767	6.783	6.772	
	0.1	0.4	6.663	6.696	6.716	6.660	6.693	6.671	
Borax	0.01	0.02	9.177	9.182	9.180	—	—	—	9.178
	0.025	0.05	9.172	9.181	9.179	—	—	—	9.167

* When two components are present, their concentrations are equal.

among the ionic activity coefficients in combinations that can be experimentally determined, such as mean activity coefficients or f_r of equation (9). These methods give equivalent results in very dilute solutions. Some of these assumptions will now be considered.

The equations of Debye and Hückel (*14*, *15*) represent observed values of the mean activity coefficients of strong electrolytes with considerable success. Thus the Hückel formula,

$$-\log f_i = \frac{Az_i^2\sqrt{\mu}}{1+Ba_i\sqrt{\mu}} - \beta_i\mu, \qquad (11)$$

might be employed to evaluate the activity coefficient of an ion i of valence z_i. In this equation, A and B are constants at a particular temperature for the water medium, whereas a_i and β_i are parameters characteristic of the mixture of ions. At ionic strengths, μ, below 0.1, the linear term can often be compensated by a small change in a_i and the logarithm of the activity coefficient expressed satisfactorily by the first term on the right alone. The magnitude of a_i is of the same order as the ionic diameter in angstroms. Although the numerical value of this parameter lies between 3.5 and 6.5 for many strong electrolytes, there is no known basis for selecting the correct value of a_i for a single ionic species.

Inasmuch as cell (7) is reversible to hydrogen and chloride ions, it would not be unreasonable to assume that the activity coefficient of chloride ion is about equal to the mean activity coefficient of hydrochloric acid in the buffer solution or in a mixture of strong electrolytes of the same ionic strength and composition with respect to cations. Unfortunately, these mean activity coefficients are often unknown. The mean activity coefficient of hydrochloric acid in its pure aqueous solution is well established, however, over a wide range of concentrations (*16*, *17*, *18*). A practical scale of paH can be defined by assuming the equality of f_{Cl} in the buffer mixture and f_{HCl} in a solution of hydrochloric acid of the same ionic strength.

Another possible approach is the separation of the measured f_r into f_{Cl} and f_{HA}/f_A. Practical considerations limit this computation to buffer systems in which HA is an anion, that is, to systems where A bears a charge different from Cl. The partition of f_r might reasonably be based upon valence relationships valid in very dilute solutions, namely,

$$f_{Cl} = f_{A^-} = f_{A^{--}}^{1/4} = f_{A^{---}}^{1/9}, \qquad (12)$$

where A^-, A^{--}, and A^{---} represent anions with 1, 2, and 3 negative charges.

Two other separation formulas are most readily described in terms of the parameters of equation (11). When the acid, HA, is a singly charged anion, it has been found that f_r^0, the limit of f_r in chloride-free solutions, can be expressed by

$$\log f_r^0 = \frac{2A\sqrt{\mu}}{1+Ba^0\sqrt{\mu}} + \beta^0\mu. \qquad (13)$$

One method of obtaining f_{Cl} assumes that a^0 and β^0 can be identified with a_i and β_i for the computation of f_{Cl} by equation (11). The other method identifies a^0 with a_i of equation (11) and drops the linear or "salt-effect" term in computing f_{Cl} in a buffer solution that contains no chloride.

These five assumptions lead to five different paH scales (*19*). When $-\log f_{Cl}$ is computed by the first term on the right of equation (11) with a value of a_i not derived from experimental data, the scale will be called p_1H. The p_2H is that unit obtained by setting f_{Cl} equal to f_{HCl} in a solution of the same ionic strength as the buffer solution. Partition of f_r according to the relationships assumed in equation (12) yields p_3H. Identification of a^0 and β^0 with a_i and β_i leads to the unit designated p_4H, whereas omission of the salt-effect term gives p_5H. The paH of buffer solutions without added chloride is thus expressed in terms of experimentally defined quantities by the following equations:

$$p_1\mathrm{H} \equiv (pw\mathrm{H})^0 - A\sqrt{\mu}/(1+Ba_i\sqrt{\mu}). \qquad (14)$$

$$p_2\mathrm{H} \equiv (pw\mathrm{H})^0 + \log f_{HCl}. \qquad (15)$$

$$p_3\mathrm{H} \equiv (pw\mathrm{H})^0 - 1/2 \log f_r^0. \qquad (16)$$

$$p_4\mathrm{H} \equiv (pw\mathrm{H})^0 - 1/2 \log f_r^0 + 3/2\ \beta^0\mu. \qquad (17)$$

$$p_5\mathrm{H} \equiv (pw\mathrm{H})^0 - 1/2 \log f_r^0 + 1/2\ \beta^0\mu. \qquad (18)$$

The relationship among these last three

paH scales is evidently given by

$$p_4H = p_5H + \beta^0\mu = p_3H + 3/2\,\beta^0\mu. \quad (19)$$

In each of these equations the superscript zero indicates that the effect of chloride has been removed by extrapolation to a pure buffer solution without chloride.

The paH at 25° C of several buffer solutions on these five scales is listed in Table 1 and compared, where possible, with the paH derived from measurements of cells with liquid junction reported by Hitchcock and Taylor (*9*) and by MacInnes, Belcher, and Shedlovsky (*11*). Inasmuch as the choice of a_i in equation (14) is partially arbitrary, two p_1H values, calculated with 4 and 6 for a_i, are given. When the ionic strength is 0.01, these differ by only 0.003 unit. The pwH of the acetate, phthalate, phosphate, and borax solutions was derived from published emf data (*19*, *20*, *21*, *22*).

It must be emphasized that thermodynamics offers as much, or as little, support for the choice of one paH scale as another. One cannot state categorically that a particular method of computation is wrong and another right. The assumptions can only be compared with respect to their reasonableness. Chloride ion evidently plays a unique role in these pH equations. None of these formulas can qualify as adequate unless it furnishes the same paH for a given buffer solution in the absence of sodium bromide or sodium iodide, for example, as it gives in the limit of zero concentration of sodium chloride. Electromotive-force measurements of hydrogen-silver halide cells containing phosphate buffer solutions with added sodium chloride, sodium bromide, and sodium iodide (*23*) offer an interesting, though not exhaustive, test of the adequacy of these five methods of computation (*19*). Both pwH and $\log f_r$ were obtained for varying ratios of halide to phosphate. The limiting values in the phosphate buffer solutions without halide were found by extrapolation. By fitting f_r^0 to equation (13), a^0 and β^0 were determined as well.

The paH of equimolal phosphate buffer solutions on the p_2H, p_3H, p_4H, and p_5H scales was computed by equations (15), (16), (17), and (18). The values on the last four scales are shown in Fig. 2 as a function of ionic strength. The lines representing these scales are labeled 2, 3, 4, and 5. The results derived from bromide cells are marked with a single prime and those from iodide cells with a double prime. Lines unmarked save for the identifying figure represent data from the chloride cells. The dots (curve 5) are the values of the NBS scale. The upper and lower dashed lines locate the p_1H curve when a_i is arbitrarily assigned the extreme values of 8 and 3 for the computation. The molality of each phosphate salt is one quarter of the ionic strength.

The three sets of p_2H values computed by equations of the form of equation (15) from $-\log (f_H f_X m_H)$, where X represents halide, and the activity coefficient of the corresponding halogen acids agree well among themselves but are from 0.01 to 0.03 unit higher than curve 5 at ionic strengths between 0.1 and 0.2. It is noteworthy, however, that all methods of calculation give essentially the same paH at low ionic strengths. The course of the true $-\log a_H$ curve can never be ascertained. Nevertheless, at ionic strengths of

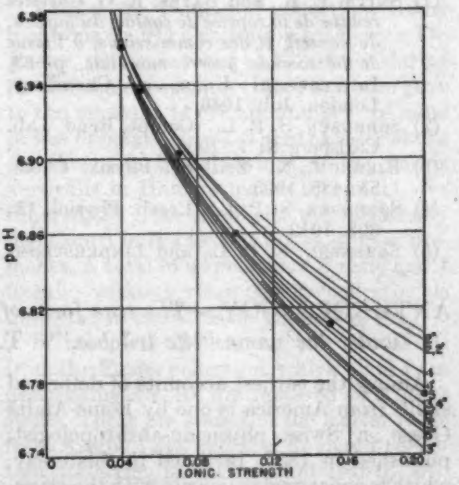

FIG. 2.—p_2H, p_3H, p_4H, and p_5H of phosphate buffer solutions as a function of ionic strength. Curves representing the four scales are labeled 2, 3, 4, and 5. The values were derived from the emf of cells with silver-silver chloride electrodes (unprimed), silver-silver bromide electrodes (single prime), and silver-silver iodide electrodes (double prime). The dashed lines indicate the course of the curve of p_1H for a_i values of 8 (upper line) and 3 (lower line). The dots (curve 5) are the NBS values.

0.01 or below, where all of these reasonable assumptions give practically identical results, the *pa*H can be said to possess some measure of thermodynamic significance.

It is evident that the *pa*H is markedly affected at high or even moderate ionic strengths by the assumption used in its evaluation. For this reason, primary standards of hydrogen-ion activity should be solutions of low salt concentration. Although the true activity is unknown at the higher ionic strengths, the NBS *p*H standards are consistent with one another over the *p*H range 4 to 9.2 at all concentrations to which the *p*H has been assigned. The NBS scale is a true scale of activity at low concentrations. At the higher ionic strengths it is best regarded as a self-consistent scale which, though based upon activity, perforce embraces an assumption not subject to experimental proof. This scale of *p*H appears to be the most convenient and useful to adopt as standard.

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ANTHROPOLOGY.—*The true form of the cranial deformity originally described under the name "tête trilobée."*[1]

T. D. STEWART, U. S. National Museum.

Among the earliest accounts of deformed skulls from America is one by Louis-André Gosse, a Swiss physician-anthropologist, published in 1855. Included in this essay, which is concerned primarily with the classification of deformity types, is the first description of a skull from Isla de los Sacrificios, a tiny island 5.5 km southeast of the port of Veracruz, Mexico. Gosse's description of this skull is of historical importance because the artificial distortion which it exhibited which he characterized as "tête trilobée" has influenced all subsequent generalizations regarding the distribution of deformity types in Middle America. Thus in Dingwall's book on cranial deformity (1931, p. 154) it is stated that—

> The skulls from Isla de los Sacrificios, near Veracruz, where the Spaniards first saw the gory remains of human sacrifice are unusually distorted, and Salas [1921, quoting Gosse] describes them as trilobed on account of the depressions doubtless left by the constricting bandages. This again suggests that at least two important forms

[1] Published by permission of the Secretary of the Smithsonian Institution. Received September 9, 1947.

of cranial deformation were known in Central America from early times, that produced by boards and that produced by bandages.

Also, Imbelloni (1934, p. 65), in plotting out the regions of deformity throughout the hemisphere, says that—

[The Quiché-Huasteca] region presents deformities of the type [*tabular erecto*], with the peculiarity of transverse grooves that, according to Gosse, facilitated the carrying of burdens (they are what Gosse calls *trilobed*). It comprises the coast of Mexico corresponding to the province of Veracruz (with the nearby Isla de los Sacrificios) and Guatemala. (Free translation.)

Recently (1943) a careful archeological investigation was made on Isla de los Sacrificios by the Mexican archeologist Wilfrido du Solier in the course of which several skulls were encountered. Through the kindness of du Solier I was able to examine these skulls during my visit to Mexico City in September 1946. So different from the classical description of Gosse is the type of deformity in these new specimens that I have reviewed the whole subject with the interesting results that follow.

HISTORICAL

According to Gosse, his description of the Sacrificios type of deformity was based upon the cast of one of several male skulls brought to France and deposited in the "Anthropological Museum of Paris" by a French naval officer named "Reymond." The cast was made by a Paris physician, Guy the Elder, and was seen by Gosse in the museum in Geneva. The peculiar trilobed shape exhibited by the cast is clearly shown in Gosse's drawings (Fig. 1).

In 1861, at a meeting of the Anthropological Society of Paris, Gosse again referred to this type of deformity; this time in connection with his paper on a deformed skull from Ghovel, Mexico. Here he uses the term "trilobée" synonymously with "occipito-sincipito-frontale." In explanation he says (1861, pp. 576–577):

The impressions left on the skull seem to indicate that the trilobed form was obtained by means of a thick compress, narrow and long, extending from the neck to the sinciput, that produced a deep depression along the median line of the occipital squama and along the posterior half of the sagittal suture, thus dividing the back of the head into two lobes. Moreover, one or two small compresses were applied on the frontal and the whole was held in place by the aid of two bands, one transverse, passing over the sinciput, and the other circular, passing around the base of the skull. (Free translation.)

Further information on this type of deformity was supplied by Hamy (1884–1891).[2] According to this author, the cast seen by Gosse had been considerably altered ("fortement remanié") and consequently the description based thereon should be modified in many important points (footnote 2, p. 91; footnote 1, p. 93). Furthermore, Hamy states that the skull from which this cast was made may have come from the Dumanoir collection (footnote 2, p. 91). This was plausible because Captain Dumanoir, who commanded the French corvette *Ceres*, explored Isla de los Sacrificios in 1841 and discovered sepulchers there containing human remains (Mayer, 1844, p. 96). However, all this is difficult to reconcile with Hamy's specific statement (p. 91) that the Dumanoir collection had not been described before 1884.

Besides the Dumanoir collection, Hamy mentions (p. 91) a collection made by a Dr. Fuzier, who excavated at Sacrificios during the French occupation (1838) and who gave to the museum "a certain number" of more or less damaged skulls. Three of these skulls are shown in line drawings of the norma verticalis in Hamy's plates 10 and 11. No other skulls from Sacrificios are specifically mentioned in the text or tables of measurements. A total of 6 specimens, 5 male and 1 female, without reference to collector, is indicated in the table on Hamy's p. 92.

In the plate illustrating the two skulls from the Fuzier collection, which plate I am designating no. 10, are featured two other skulls. These are stated in the legend to be from Sabine Lake and the Reynaud collection. Referring to the relevant text (p. 98), we find that—

[2] This publication appeared in three parts between the dates given. Most bibliographies list it as incomplete, perhaps because plate no. 18 is missing. It does not appear that this plate ever was printed. Moreover, two plates are given the number 10, whereas none bears the number 12. I have assumed from the wording of the text that the plate illustrating the skulls from Sacrificios and Sabine should be no. 10.

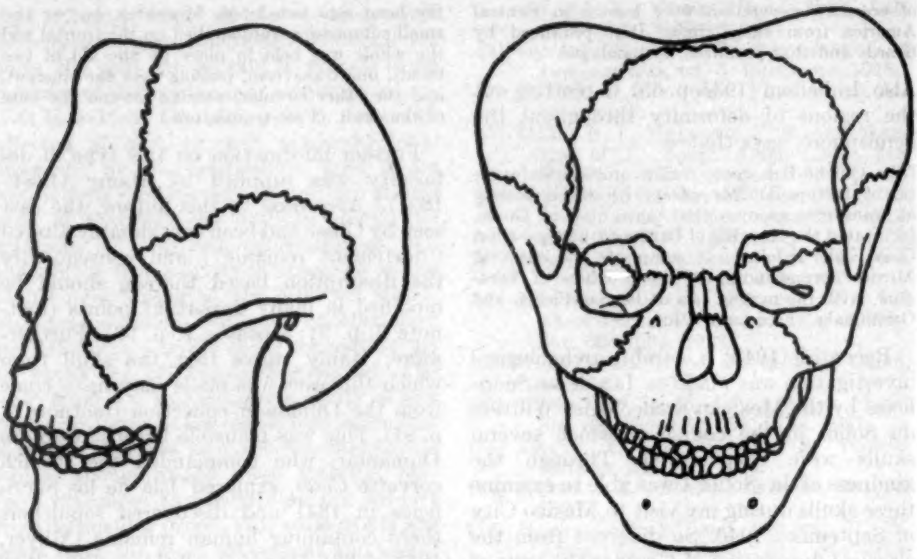

FIG. 1.—Two views of the cast of a deformed skull from Isla de los Sacrificios, Mexico, as illustrated by Gosse in 1855 (pl. 1, figs. 4[a] and 4[b]).

The skulls offered to the Museum of Natural History of Paris by Admiral Reynaud under the name of *skulls from Sabine Gulf of Mexico* do not differ sensibly from those of the second type from the island of Sacrificios.[3]

Footnotes 3 and 4 on the same page offer the additional information that these skulls—

> . . . for a long time have been confused under the name of *Sacrificios*, but their primitive label is such that we came to transcribe it. Sabine is the name of a gulf and of a river which forms the boundary between Texas and Louisiana.
>
> Our first type of Sacrificios was not encountered among these skulls. (Free translation.)

Line drawings of one of the skulls said to have come from Sabine are shown in Fig. 2.

Readers will recall that Gosse attributed the original of his cast to the collection of a naval officer named "Reymond." This name is remarkably similar to that of the admiral, Reynaud, who, Hamy says, made the Sabine collection, which was believed for a long time to have come from Sacrificios. Could it be, therefore, that one of these names is an erroneous spelling and that the same collector is referred to? If so, did Gosse really describe a skull from Sabine instead of from Sacrificios? Or is Hamy in error in changing the locality of the collection from Sacrificios to Sabine? These are important questions, because if it can be proved that this deformity type occurs as far north on the coast of the Gulf of Mexico as the boundary between Texas and Louisiana, another cultural link between Mexico and the southeastern United States will have been established.

Further search in the literature has brought to light two references that clarify this subject somewhat:[4] (1) In Larousse's *Grand dictionnaire universel du XIX[e] siècle* (1875, vol. 3, p. 1136) there is a biography of a distingusihed French naval officer by the name of Aimé-Félix-Saint-Elme Reynaud who began his maritime career in 1827. In 1850 he became Captain of a frigate and in 1864 a Vice-Admiral. This biographical dic-

[3] Hamy's second type of deformity corresponds to Gosse's "tête trilobée." Hamy's first type is based upon a single specimen and differs merely in having a greater compression of the frontal bone.

[4] I am indebted to Mrs. Elizabeth H. Gazin, U. S. National Museum librarian, for locating these references.

tionary fails to list a "Reymond." (2) A footnote to a paper by Serres (1855, footnote 1, p. 46) reads in part as follows:

> The ideal beauty that the Aztecs sought to produce was favored by the normal elongation of the bones of the skull and face of this tribe. By compression they only exaggerated their normal type. *This is true also of the skulls which for the first time have been given to the museum by Reynaud, distinguished officer of the French navy and so far found only in the island of the sacrifices, in the Gulf of Mexico.* All of the bones of the skull and face are large, the inverse of the preceding. The compression thus was exerted in inverse sense; it was for the purpose of enlarging the skull and giving it the trilobed form that they represent .... (Free translation; italics mine.)

Since Serres' paper was published in the same year—1855—as that by Gosse, and both he and Gosse refer to a collection of skulls from Sacrificios given earlier to a Paris museum by a French naval officer, it seems reasonable to believe that they are speaking of the same event.[5] Furthermore, since Serres gives this officer's name as "Reynaud" and there was a distinguished French naval officer by that name living at that time, whereas Gosse gives this officer's name as "Reymond," for which there is no corresponding biographical record, it seems likely that Gosse misspelled the name. Such misspelling is understandable because in longhand a's may look like o's, u's like n's, and m's like n's.

What is still not explained is the later confusion as to the provenience of this collection. It seems to have been well established in 1855 that Reynaud obtained it from Sacrificios. And yet in 1891 Hamy reports the old label as reading "crânes de Sabine, gulfe du Mexique." In view of the improbability that a French naval officer would have an opportunity just prior to 1855 to carry out archeological excavations in the region of Sabine Lake (Texas-Louisiana) and in view of the subsequent failure to recover other skulls thus deformed from either Texas or Louisiana, I believe that Hamy was wrong in attributing the Reynaud collection to the Sabine. Therefore, I regard these skulls not only as exhibiting a type of deformity characteristic of Sacrificios, as Hamy admits, but as actually coming from that place.

[5] Gosse (1855, Paris ed., p. 40) states that Prof. Serres gave him permission to examine the specimens in the anthropological museum.

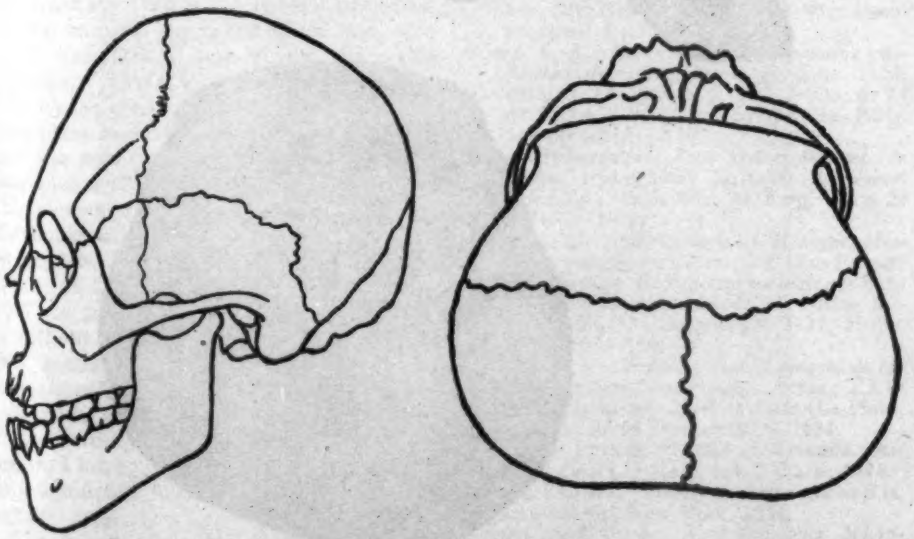

FIG. 2.—Two views of deformed skull no. 5 from the Reynaud collection believed by Hamy to have come from Sabine Lake on the Texas-Louisiana boundary. Redrawn and reoriented from Hamy's illustrations of 1884–91 (pl. 10, figs. 1 and 3).

DEFINITION OF TYPE

Taking into account this decision, let us now summarize what is known about the skulls from Sacrificios. All these, except for the new finds of du Solier, seem to be in Paris and to total at least 15. The early collectors, who visited the island around the years 1838–1841, were Dumanoir, Fuzier, and Reynaud. The only firsthand descriptions of the deformity are by Gosse (1855) and Hamy (1884–1891). These descriptions seem to be based upon extreme cases, for both Gosse and Hamy admit that the artificial characteristics are less pronounced in the majority of cases than they have described them. Thus there is good reason to believe that the skull shown in Fig. 2, which was illustrated originally only because it was believed to come from Sabine rather than from Sacrificios, is more typically deformed. So far as I can discover from the descriptions, only one skull has the curious projection of the upper part of the frontal bone illustrated by Gosse (Fig. 1). This one specimen seems to have furnished the excuse for the name "tête tri-

FIG. 3.—Two views of a deformed skull collected by du Solier in 1943 on Isla de los Sacrificios, Mexico. (Photographs supplied by the Museo Nacional of Mexico.)

lobée" under which this deformity is generally known.

If we ignore this extreme case, the deformity can be recognized by the following characteristics: (1) When the skull is held in the Frankfort position the vertex or highest point is at or near bregma; (2) looked at from above, the skull is very broad, sometimes broader than long; (3) the posterior parietals are pressed downward and forward, sometimes with accompanying compression of the frontal and/or occiput (the latter tending to assume a vertical plane); and (4) there may be more or less of a depression along the sagittal suture and behind the coronal suture. A skull deformed in this manner suggests that it has had its growth restricted along the midline of the vault and consequently that expansion took place laterally, Also, when compression is high upon the parietals the skull appears to have a low vault.

The skulls recovered by du Solier are not markedly distorted. Indeed, the lateral view of the skull shown in Fig. 3 looks undeformed. This is due to the fact that the flattening of the posterior parietals in this case is asymmetrical (see vertical view) and the least involved side has been presented to the camera. As a matter of fact, this skull illustrates, if not ideally, the really significant element of the Sacrificios deformity type; namely, the inclined compression plane involving the posterior parietals and the upper part of the occipital. In accordance with current custom I am calling this element of the deformity "lambdoid" flattening, although it might with more accuracy be called "obelionic" (Stewart, 1939). As I have shown elsewhere (Stewart, 1947; in press), lambdoid flattening, with or without frontal and/or occipital compression, made its appearance in late prehistoric times throughout a large part of Mexico. Having seen numerous skulls with lambdoid deformity from other late sites in this region, I have no doubt that this is the true and significant form of the Sacrificios deformity type.

The so-called lobation (double or triple) which is present in extreme cases of the deformity and which Gosse stressed, appears to be a secondary feature. Owing perhaps to the pattern of cranial growth under artificial restraint there is present sometimes a postcoronal depression and a depression along the sagittal suture. The opposite condition, an expansion, usually characterizes the midparietal parts in these cases. Thus the effect is that of lobation. Because some lobation can be found in all classes of deformity and wherever deformity was practiced, I attribute it to altered growth processes rather than to direct pressure from longitudinal and transverse constricting bands.

In view of what is here pointed out, generalizations regarding the distribution of deformity types, such as that of Imbelloni, are misleading where they have to rely upon early descriptions of atypical specimens and where the chronological sequences have not been worked out.

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BOTANY.—*Studies in* Lonchocarpus *and related genera, III:* Humboldtiella *and* Callistylon.[1]

FREDERICK J. HERMANN, U. S. Department of Agriculture.

Next to *Willardia* the two plants most frequently confused with *Lonchocarpus* in America are *Humboldtiella ferruginea* (HBK.) Harms and *Callistylon arboreum* (Grieseb.) Pittier. Belonging as they do to the tribe Galegeae, both of these shrubs or small trees of arid open or sparsely wooded slopes, coasts, and roadside thickets are readily separable when bearing mature fruit from *Lonchocarpus* and other genera of the Dalbergieae by their dehiscent pods. Their alternate (occasionally subopposite) leaflets likewise distinguish them from *Lonchocarpus*. But, like many tropical shrubs, they have a tendency to drop both pods and leaves toward the end of the dry season and to burst into flower with the first rains, generally before the new leaf-buds have begun to expand. This leafless flowering stage is particularly attractive to collectors, and the superficial resemblance between their inflorescences and those of some of the Lonchocarpi accounts for the large number of specimens in herbaria referred at least tentatively to the latter genus. In this leafless condition both plants seem to be most readily separable from *Lonchocarpus* by their persistent, indurated, awl-shaped stipules, by the lack of evident bractlets, and by the conspicuous articulation of the pedicels at both base and apex. The calyx, with its deep tube, its comparatively long teeth, and its subbilabiate form, so pronounced in the bud, might also be considered diagnostic.

The combination of the half-dozen or so characters, for the most part of fundamental taxonomic significance, here listed for setting off these two plants from *Lonchocarpus* is found in both the monotypic genera *Humboldtiella* and *Callistylon*. Such an apparently fortuitous combination of characters occurring simultaneously in supposedly separate genera naturally raises the question of their status, and an examination of their history reveals that in each case this has had a varied career.

First known of the two was *Humboldtiella*, originally described by Kunth in Humboldt and Bonpland's *Nova genera et species plantarum* (6: 395. 1823) as *Robinia* (?) *ferruginea*. The basis of Kunth's description was a fragmentary flowering specimen, lacking leaves and fruit, collected by Humboldt or Bonpland in the Quebrada de Tacagua near Caracas, Venezuela, and deposited in the quondam Berlin Herbarium (Field Museum photograph no. 2079). In 1924 Harms (Fedde Repert. Spec. Nov. 19: 12–14) pointed out its departure from *Robinia*, in its rostrate carina and narrow pod with unmargined lower suture, and from *Coursetia*, which does possess these characteristics, in its broad, short calyx-teeth and its coalesced vexillar stamen. Because of these discrepancies he proposed for it the new genus *Humboldtiella*. Pittier, however, maintained (Journ. Washington Acad. Sci. 18 (8): 209. 1928) that the only character that would exclude it from *Robinia* "is the absence of a conspicuous margin on the upper suture of the pod, which would certainly not be sufficient to establish a new genus"—a conclusion difficult to reconcile with the fact that the plant differs from *Robinia* in possessing monodelphous stamens, a thick, fleshy calyx with short, relatively blunt teeth, and articulate pedicels, in addition to the rostrate keel noted by Harms. At any rate, Pittier seems to have abandoned his original low opinion of the merits of *Humboldtiella* for generic recognition, since in his latest work on the subject (*Leguminosas de Venezuela*,

[1] Received August 7, 1947.

I—Papilionaceas. Boletín Técnico No. 5, Ministerio Agric. y Cría, Caracas, 1944) we find (p. 152): "Como lo había hecho entrever el Dr. Harms, hace algunos años, la planta que acabamos de definir no pertenece realmente al género Robinia. Difiere principalmente en la forma del cáliz y de las semillas, en la ausencia de un ala en la sutura superior de la legumbre y en otros detalles."

The second plant, the Colombian "*Ramoncillo*," was originally described as *Coursetia arborea* by Grisebach (*Flora of British West Indies*, 183) in 1859. Harms considered it, or at least such material of it as was available to him, to be sufficiently close to *Robinia ferruginea* to be relegated to its synonymy in his transfer of the latter to *Humboldtiella*. This fact seems to have been overlooked by Pittier when he expressed surprise at finding *Coursetia arborea* among the numbers cited by Harms under his *Humboldtiella ferruginea* (*l.c.*, 208–209). His own comment ("Later, when revising the Papilionatae for the Venezuelan Herbarium, I was surprised to find that, among the numbers cited by Dr. Harms as belonging to his *Humboldtiella ferruginea*, one (no. 5780) apparently corresponds to *Gliricidia sepium* HBK., another (no. 9078) is unmistakably *Coursetia arborea* Griseb., and only one (no. 6004) belongs to the real *Robinia ferruginea* HBK . . . ") seems to be a more fitting basis for surprise not only because one would logically expect to find *Coursetia arborea* (*Pittier 9078*) cited under *Humboldtiella ferruginea* when treated as a synonym of that species but also because at least the specimens in the U. S. National Herbarium of the other cited numbers bear out Harms's rather than Pittier's determinations, that is, *Pittier 5780* shows no resemblance to *Gliricidia* but is typical *Robinia ferruginea*, while *Pittier 6004* is *Coursetia arborea*, not *Robinia ferruginea*. Following his criticism of Harms's work, Pittier proposes segregating *Coursetia arborea* as the type of a new genus, *Callistylon*. In the proposal of *Callistylon*, its distinctiveness from *Coursetia* is carefully elaborated; but no reference is made to its relationship with *Humboldtiella* until the necessity of keying out both genera arose in the *Leguminosas de Venezuela*. Here we find (*l.o.*, 139–140, 152) carried still further a confusion in the characters of *Humboldtiella* and *Callistylon*, which was already apparent in the original publication of *Callistylon*. In the proposal of *Callistylon* the lateral calyx teeth are described as more or less acute and the lowermost tooth as acute, whereas a new description of *Robinia ferruginea* accompanying the same paper states that the calyx teeth in that plant are obtuse. Exactly the reverse is true, however, as is apparent from Kunth's original description of *Robinia ferruginea* (Humboldt & Bonpland 6: 395) as having the calyx "lobis . . . acutis" and from an examination of a photograph of the type specimen. In the generic key to the Venezuelan Papilionatae this inversion is perpetuated as "Dientes del cáliz cortos y todos obtusos . . . " for *Humboldtiella*, and "Dientes del cáliz alargados o desiguales, pero siempre el carinal largo y agudo . . . " in the lead for *Callistylon* and *Coursetia* together. The lead setting off *Callistylon* from *Coursetia* describes the calyx teeth as "muy desiguales, los 2 superiores obtusos y unidos, los laterales más cortos y agudos, el inferior otra vez más largo y agudo," but it is only in the bud stage that the teeth could strictly be called very unequal and the lateral teeth shorter than the upper pair. In flowering and fruiting material of typical *Callistylon arboreum* the calyx teeth are subequal, the lateral and lower ovate and obtuse to semiorbicular rather than deltoid and acute as in typical *Humboldtiella ferruginea*. The original description of *Callistylon* calls for a plant with leaflets "petiolulatis . . . exstipellatis," whereas the petiolules are actually stipellate, and describes the style as glabrous as opposed to "basi glabro apicem versus utrinque villosulo," whereas the villosulous character applies equally well to the styles of both plants. *Callistylon* is originally described as having "bracteolae parvae et inconspicuae," but the generic description in Pittier's later treatment specifies "bracteas y bracteolas nullas." Diligent search of the 38 sheets of *Callistylon* available to the writer has failed to reveal any trace of bractlets, but the bracts, although caducous, are fully as conspicuous

during most of the bud stage as are the equally evanescent bracts of *Humboldtiella ferruginea*. *Callistylon* is keyed out from *Coursetia* in *Leguminosas de Venezuela* by the additional character of having "valvas de la legumbre de dehiscencia plana y no elastica," yet the elastic dehiscence of the pods in the Pittier collections of *Callistylon* numbered *7833*, *10780*, and *11447* (the last cited under the original description) could not be more striking.

There can scarcely be any question that the peculiarities of the calyx alone in *Callistylon* are sufficient to set it off generically from *Coursetia*, just as the calyx morphology in *Humboldtiella* is adequate basis for removing *H. ferruginea* from *Robinia*. But between *Humboldtiella* and *Callistylon* there appears to be no distinguishing character of generic rank. The treatment of the two plants by Harms as specifically indistinguishable, and Pittier's inability to consistently separate the two as evidenced by his citation of his collection *6004* (typical *Callistylon arborea*) under *Robinia ferruginea*, would seem to be significant corroboration of this view. It is therefore proposed that the genus *Callistylon* be abandoned, and that *Coursetia arborea* be transferred as follows:

Humboldtiella arborea (Griseb.) Hermann, comb. nov.

Coursetia arborea Griseb., Fl. Brit. W. Ind. 183. 1859.

Callistylon arboreum (Griseb.) Pittier, Journ. Washington Acad. Sci. 18 (8): 212. 1928.

The submergence of this species in *Humboldtiella ferruginea* by Harms is not difficult to understand when one considers the prevalence of collections which are annoyingly intermediate between the two. Of the 53 collections of *Humboldtiella* in the U. S. National Herbarium, 7 can be conscientiously referred to *H. ferruginea*, 38 may be with varying degrees of confidence assigned to *H. arborea*, but 8 are too nicely balanced between the two to justify outright committal in favor of one or the other. On the other hand, the differences between the typical forms of both plants (well illustrated in plates 80 and 81 in Pittier's *Leguminosas de Venezuela*) are too fundamental to permit of their being interpreted as mere ecological extremes of a single polymorphic species, nor is there a geographic segregation of the two sufficiently marked to warrant their designation as varieties (i.e., "subspecies," as currently employed with increasing frequency). A hypothesis of hybridization between the two species, and that of a contemporaneous, fertile and vigorous type, would seem to be the most plausible explanation of the frequency of these transitional forms and the comparative impurity of many of the forms identifiable as possessing predominantly the characteristics of one of the extremes. Geographically the specimens of *H. arborea* at hand represent localities scattered throughout most of northern South America north of latitude 5°, from the Department of Bolívar, Colombia, eastward to Trinidad and the Kanuku Mountains in British Guiana; *H. ferruginea* is almost restricted to the Venezuelan North-Central States of Yaracuy, Carabobo, Aragua, Distrito Federal and Miranda, with one outlying station in Sucre; and the intermediates are apparently centered in two disjunct areas, in the Venezuelan North-Central States where the ranges of the putative parents overlap and on Trinidad and the extreme eastern tip of the Paria Peninsula in Sucre, Venezuela. The nearest authenticated specimen of *H. ferruginea* is from a locality approximately 80 miles west of this second area of extensive hybridization, although Pittier cites two Trinidad specimens that are not available for verification. Harms cites a Brazilian collection under his *H. ferruginea*, as well as reports for Panama and Guiana, but his concept, of course, included both species.

The following key is an attempt to emphasize the more constant characters by which the two species may be separated. Pronounced departures from these distinctions are indicated in the citations of collections below.

Calyx slightly if at all gibbous, generally tapering toward base, averaging 6 mm in length, densely ferruginous-strigose, *tube 1½ to 2½ times length of lateral teeth*; calyx-teeth typically deltoid, acute, lateral averaging 2 mm long; leaflets generally elliptic-lanceolate to oblong-lanceolate, broadest below middle, acute, sparsely strigose above, pilose-strigose beneath..... *H. ferruginea*

Calyx typically gibbous on vexillar side, generally rounded at base, averaging 5 mm in length, with thinner and paler pubescence, *tube 3½ to 4 times length of lateral teeth*; calyx-teeth typically ovate to semiorbicular, obtuse, lateral averaging 1 mm long; leaflets generally oval-elliptic to oblong, broadest at middle, obtuse, typically glabrous..... *H. arborea*

SPECIMENS EXAMINED

(All in U. S. National Herbarium, except Steyermark collections in Chicago Natural History Museum)

HUMBOLDTIELLA FERRUGINEA

VENEZUELA: *Ll. Williams 12331*, La Entrada, Carabobo (typical); *Pittier 7594*, between El Encanton and Los Teques, Aragua (typical); *Pittier 9159*, between La Victoria and Los Teques, Aragua (calyx-lobes mostly obtuse); *Pittier 5780*, La Trinidad de Maracay, Aragua; *F. Tamayo 1305*, near Guayas, Aragua; *Pittier 11956*, Los Moriches, Miranda; *A. Allart 283*, near Las Moriches, Miranda; *A. Allart 283*, near Las Mostazas, Miranda (calyx pale); *Steyermark 62403*, between Cumanacoa and Cocollar, Sucre (calyx-tube nearly 4 times the length of lateral teeth).

HUMBOLDTIELLA ARBOREA

COLOMBIA: *R. D. Metcalf 30017*, between Medillín and Antioquia, Antioquia; *Dugand & Jaramillo 2849*, between Cartegena and Turbaco, Bolívar; *H. M. Curran s. n.*, Apr.–May 1916, Island of Mompos, Bolívar; *Bro. Elias 1192*, Puerto Colombia, Atlantico; *Dugand 1181 & 323*, Barranquilla, Atlantico; *Dugand & Jaramillo 4042*, between Juanmina and Cuatrobocas, Atlantico; *Dugand 3640*, Juanmina, Atlantico; *H. H. Smith 935*, Santa Marta, Magdalena (calyx-lobes acutish).

VENEZUELA: *Pittier 10780*, near Valera, Trujillo; *Pittier 13125*, Escuque, Trujillo; *F. Tamayo 1694*, Valera, Trujillo; *Saer 230*, La Ruesga, Lara; *Saer 247*, Barquisimeto, Lara (indument ferrugineous); *A. Jahn 1197*, Humocaro, Lara; *Pittier 7665*, between Valencia and Puerto Cabello, Carabobo (typical); *Pittier 9078*, between Puerto Cabello and San Filipe, Carabobo (calyx-lobes unusually acute); *Pittier 9413*, same, in fruit (calyx-lobes blunt); *Pittier 7631*, near Valencia, Carabobo; *Pittier 10310*, between Caracas and La Guaira, Dist. Federal; *Killip & Tamayo 37053*, Santa Lucía, Miranda; *Pittier 6004*, Siquire Valley, Miranda (typical); *Pittier 7833*, Guatire, Miranda; *Pittier 11447*, El Sombrero, Guárico; *Archer 3025*, between El Sombrero and La Democracia, Guárico (typical); *Ll. Williams 12566*, El Cristo, Bolívar (calyx acute at base); *Steyermark 61488*, Bergantín, Anzoátegui; *Brown, Gillin & Bond 21*, Paria Peninsula, Sucre; *Broadway 796*, Cristóbal Colón, Sucre; *Broadway 809*, same (typical).

TRINIDAD: *Britton 478*, Teteran Bay; *Britton 485*, same (leaflets broadest below middle); *Britton, Hazen, & Mendelson 523*, Patos Island; *Britton, Freeman, & Watts 2704*, Chacachacare; *A. Fendler* in 1877–1880, without definite locality; *Britton & Broadway 466*, Lady Chancellor Road.

BRITISH GUIANA: *A. C. Smith 3092*, Kanuku Mountains.

HUMBOLDTIELLA ARBOREA × H. FERRUGINEA

VENEZUELA: *Pittier 12601*, San Pedro, Yaracuy (calyx nearest *H. arborea;* leaflets nearest *H. ferruginea*); *Pittier 8196*, between Puerto Cabello and San Esteban, Carabobo (calyx proportions of *H. arborea*, but lateral teeth rounded-deltoid; indument dense, dark); *Ll. Williams 10400*, Carmen, Aragua (calyx gibbous but tapering at base, densely hairy, the tube only twice the length of the acute lateral lobes; leaflets of *H. arborea*); *Broadway 266*, Cristóbal Colón, Sucre (calyx proportions of *H. arborea* but teeth nearly deltoid, varying to broadly obtuse; leaflet shape and size of *H. ferruginea*, but glabrous); *Broadway 813*, same (calyx proportions of *H. ferruginea* and lateral lobes acute, but vesture pale; leaflets blunt, not broadest below middle).

TRINIDAD: *Broadway s. n.*, March 7, 1930 (lateral calyx-teeth deltoid but the tube 4 times their length; indument pale); *Broadway 3819*, without definite locality (calyx proportions intermediate, the tube 3 times the length of the lateral teeth; leaflets blunt, but broadest below middle); *N. L. & E. G. Britton 2201* coastal thicket (calyx teeth deltoid but tube 3½ times as long).

ZOOLOGY.—*Some interesting starfishes and brittle-stars dredged by the* Atlantis *in the mid-Atlantic.*[1] AUSTIN H. CLARK, U. S. National Museum.

The Woods Hole Oceanographic Institution has recently submitted to me for examination, through Dr. Louis W. Hutchins, a small but interesting collection of starfishes and brittle-stars dredged by the *Atlantis* in the mid-Atlantic. The expedition on which these were found, Cruise No. 150 of the *Atlantis*, was sponsored by the National Geographic Society, Columbia University, and the Woods Hole Oceanographic Institution. I am much indebted to the Institution and to Dr. Hutchins for the privilege of studying this collection.

The species represented in the collection are the following:

Hyphalaster parfaiti E. Perrier

Locality.—Atlantis station 15; mid-Atlantic west of Gibraltar (lat. 35° 37′ N., long. 30° 51′ W.); 3,200 meters; August 16, 1947. Seven specimens.

Notes.—The details of the seven specimens are as follows:

[1] Contribution from the Woods Hole Oceanographic Institution No. 410. Published with the permission of the Secretary of the Smithsonian Institution. Received November 5, 1947.

Specimen	*R*	*r*	*Cribriform organ*	*United marginals*
1	34 mm.	14 mm.	7	10
2	34	13	9	10
3	33	14	5	9
4	30	11	7	8
5	27	11	7	8
6	17	8	7	4
7	17	7	5	4

Pythonaster atlantidis n. sp.

Description.—$R = 165$ mm, $r = 28$ mm. The height at the center of the abactinal system is 26 mm. The rays are 31 mm wide at the base, tapering rapidly to 10 mm at 30 mm from the base, from this point tapering gradually to 3 mm at the tip. A shallow interradial sulcus runs from the middle of each interradius to the center of the disk. The animal may be described as broadly stellate, with each point of the star produced into a long and slender arm.

There is no abactinal skeleton, but the skin is filled with minute rounded plates, which are almost contiguous on the disk and arm bases but become scattered on the outer part of the arms. Among these are the much larger and denser circular lenticular plates, which carry the groups of spines.

On the midline of each ray, running from the center of the disk to the end of the swollen portion of the arm bases, is a band 10–15 mm wide consisting of groups of from 2 or 3 to about 10, commonly 5 or 6, very slender and delicate spines 2–3 mm long arising from a common base on a deeply embedded lenticular plate, the whole enclosed in a bag of thick skin by which the spines are entirely concealed. In a patch about 15 mm long on the inner part of the disk these spine-containing sacculi are intermixed with papulae. On the disk this band of sacculi is bordered on each side by a patch of bare skin through which the large eggs, 2 mm in diameter, are visible. These bare patches may bear two or three sacculi including 4–7 spines. The apical region is closed by 5 large radially placed triangular flaps consisting of numerous delicate spines enclosed in a web of thick skin. The madreporite is situated at the inner end of an interradial sulcus at the outer end of the line between two of these valves or flaps. Just beyond the central valves and bordering the interradial sulcus for about half its length are a few cup-shaped structures consisting of about a dozen slender spines radiating upward from a common base and enclosed in thick skin.

The arms beyond the swollen basal portion are in cross section triangular with the apex rounded, about as high as broad, becoming higher than broad toward the arm tips.

The adambulacral plates have a strongly curved crest which is set at an angle of about 60° with the axis of the arm, the distal end of each crest being considerably farther inward than the proximal end of the crest following. These crests carry a row of 8–10 slender spines which are closely placed with their swollen bases contiguous and are united by a web; the innermost spines are about 1 mm long, those following gradually increasing in length to the outermost, which is 3 mm long. The outer part of each adambulacral plate bears a single much stouter spine 4 mm long, these stouter spines supporting a broad fin-like web which runs along the actinolateral border of the arm resembling the actinal web of many Pterasteridae. Beyond the proximal swollen portion of the arms the adambulacral spines become reduced in number, being usually 5.

Running upward from each adambulacral plate to the dorsolateral border is a band about 1.5 mm broad composed of numerous fine spines arising in small groups, sometimes singly, from a row of independent concretions, the whole band being enclosed in a continuous envelope of thick skin. Beyond the swollen proximal portion of the ray the bands of the two sides meet in the middorsal line. Distally these bands become narrower, the concretions bearing only 1–3 spinelets.

The pair of mouth plates is 9 mm broad at the mouth edge, 2 mm broad on the outer border, and 7 mm long. The line of union of the two plates is raised into a rounded crest. The inner border at the mouth edge is everted and curved, and the outer borders are somewhat concave. The everted inner border of each mouth plate bears 4 large spines, beyond which are 5 much smaller spines. There are no spines on the actinal surface. The mouth plates recall those of some of the Pterasteridae, as for instance *Hymenaster perissonotus*.

The mouth is circular, 23 mm in diameter. The very large stomach is empty. The tube feet, in two series, are large and stout and end in a large sucking disk.

On the arms beyond the swollen basal portion the ambulacral plates are long and slender. The sides of the lower half diverge gradually so that the end adjoining the adambulacrals is

about 2 mm broad, the central portion of the plate being only 0.5 mm wide. The upper third of the ambulacrals is abruptly broadened in the form of a broad Y with very thick arms. When viewed from the exterior the distal arm of the Y is entirely concealed by the proximal arm of the Y of the ambulacral following, which imbricates over it. This causes the ambulacrals when viewed from the exterior, to appear abruptly bent proximally, but when viewed from the interior they are seen to be straight with both arms of the Y about equal.

The adambulacrals as viewed from the actinal edge are seen to be narrowly rhombic, about 3 mm long and 0.75 mm wide. The inner side of the lower angle of the rhombic figure is abruptly swollen, appearing as if a rather thick flat pad had been soldered to it. The distal edge of this pad is evenly curved and bears the spines that form the adambulacral comb. The stout adambulacral spine is situated at about the middle, and widest part, of the adambulacral plate at some distance from the comb-bearing pad and entirely out of line with it. The adambulacral plates are strongly imbricated so that the large spine is in line with the spines of the comb of the plate following, to which it appears to belong unless the arm is cleaned, when its true relationship becomes apparent.

Just above each adambulacral and parallel to its long axis, lying practically on its surface, there is a long, slender and delicate plate 4 or 5 times as long as broad, and a little over half as long as the adambulacral; in some cases there are two of these lying closely side by side. These plates appear to be vestigial marginals.

In a line from these vestigial marginals to the midradial line, as viewed from the inner surface of the skin, there is a regular row of elongate sharply carinate plates 2 or 3 times as long as broad closely placed with their long axes parallel. Between these regular columns of elongate plates (from the center of which on the outer side spines arise) there are very numerous and closely packed minute concretions.

Distally the plates in these columns become smaller, fewer, and more widely spaced, and the concretions become more widely scattered.

Locality.—*Atlantis* station 15; mid-Atlantic west of Gibraltar (lat. 35° 37′ N., long. 30° 51′ W.); 3,200 meters; August 16, 1947. One specimen (type, U.S.N.M. No. E. 7175).

Notes.—The genus *Pythonaster*, the sole genus in the family Pythonasteridae, includes only the type species *Pythonaster murrayi* Sladen described from a single specimen dredged by the *Challenger* at station 323 east of Buenos Aires, Argentina, in 1,900 fathoms, on February 28, 1876.

The type specimen of *P. murrayi* is slightly smaller than the type specimen of *P. atlantidis*, and the bases of the rays are much less swollen; but this difference may be due to the occurrence of large masses of eggs in the type of *B. atlantidis*.

According to Sladen's description and figure the actinolateral areas of *P. murrayi* are traversed by regular rows of isolated skin sacks, whereas in *P. atlantidis* these skin sacks are coalesced into continuous lines. The skin sacks on the abactinal surface of *P. murrayi* are much smaller and more widely separated than those of *P. atlantidis* in which they are almost or quite in contact.

In *P. murrayi* the adambulacral combs are composed of about 6 spines the number becoming reduced to 5 distally. In *P. atlantidis* there are 8–10 proximally, 5 distally. In *P. murrayi* the outermost and largest spine on the adambulacrals is counted as one of the comb, being united to the next by a web. In *P. atlantidis* the outermost spine on the adambulacrals is abruptly larger than the others and relatively much larger than in *P. murrayi* and is joined to the outermost spines on each side by a web, all the spines together and the web forming a continuous broad actinolateral web or fin which appears to be absent in *P. murrayi*.

The mouth plates of *P. murrayi* as figured are not of the same shape as those of *P. atlantidis*. They bear 3 or 4 large inner mouth spines and 3 small outer ones instead of 4 large and 5 small as in *P. atlantidis*. Furthermore, there are in *P. murrayi* spines on the actinal surface of the mouth plates which are not present in *P. atlantidis;* however, in the latter these may have been rubbed off during capture.

With only a single specimen of each species it is impossible to form any idea of the limits of variation. It is possible, though not probable, that *P. atlantidis* is a more fully developed example of the species represented by *P. murrayi*. It is also possible, though not probable, that *P. atlantidis* is a female of the species of which the type of *P. murrayi* is the male; but Sladen did not give the sex of his specimen.

Asteroschema inornatum Koehler

Locality.—*Atlantis* station 6; mid-Atlantic east of Bermuda (lat. 30° 06′ N., long. 42° 08′ W.), 1,554 meters; August 8, 1947. One specimen.

Notes.—As the original description of this species was brief and lacking in detail the following supplementary information derived from the present specimen may be of interest:

The disk is 6 mm in diameter, stellate with truncated angles and regularly incurved interradial borders; the outer ends of the radial shields are raised about 0.75 mm above the arm bases. The arms are about 60 mm long, slender, 1.3 mm broad at the base and tapering gradually to a delicate tip; they are only slightly higher than broad.

The disk is covered rather thickly with minute granules of coarse and spongy structure. The radial shields are rather broad, widest in the middle, the outer border having a broadly obtuse median angle, and those of each pair are almost in contact. They extend inward for about two-thirds distance to center of disk.

The first two tentacle pores have no scales. The next five have a single tentacle scale. Those following have two scales of which the large inner scale is about a segment and a half in length. At the arm tip the outer scale is only slightly longer than the inner, but neither assumes a hooklike shape. The larger inner scale is cylindrical in the basal third or fourth, from that point being less dense and tapering to the tip. The distal three-fourths bears on the outer side numerous long and slender sharp spinelets, longest near the tip, which through the dried skin appear as small conical points. There are similar but smaller spinelets on the inner side. The small outer scale is similarly armed.

There are 5 stout triangular teeth.

On the sides of the jaw plates within the mouth there are about 8 rather large and well separated granules; these are irregularly scattered, the group as a whole running upward and outward, the outermost being a pair, one on each side of the uppermost tooth.

The skin of the arms contains large delicate filmy plates that appear to form an almost continuous pavement.

The color in alcohol is pale dull pinkish, becoming dark purple on the outer half or more of the tentacle scales.

This species was described by Prof. René Koehler (1907) on the basis of two specimens dredged by the *Talisman* in the Gulf of Gascony (the inner part of the Bay of Biscay) (lat. 45° 59′ N., long. 6° 29′ W.) in 1,480 meters, coral bottom, on August 30, 1883. Sanderson Smith (1888) gives this station as No. 156. Koehler gave the color in alcohol as white.

A single specimen was subsequently dredged by the *Princesse-Alice* at station 2248, in lat. 37° 02′ 30″ N., long. 27° 35′ W., in 1,478 meters, on September 6, 1905 (Koehler, 1909). In his report on the *Princesse-Alice* echinoderms Koehler did not amplify his original description, but he gave a colored figure showing the animal as deep pink, lighter on the radial shields and becoming lighter on the arms after the basal 20 mm.

Ophiura inornata (Lyman)

Locality.—*Atlantis* station 15; mid-Atlantic west of Gibraltar (lat. 35° 37′ N., long. 30° 51′ W.); 3,200 meters; August 16, 1947. Seven specimens.

Notes.—In these specimens the oral shields are in most divided into two elongate plates meeting in the median line as an angle of about 90°. The jaw plates, the adoral shields, and the two sections of the oral shields are similar, and of about the same size, appearing as three similar chevrons.

In a small specimen one of the oral shields is undivided. In other cases it appears as if the third or outer chevron was composed in reality of a pair of supplementary plates intercalated between the oral shield, much reduced in size, and the adoral shields.

Opiomusium armigerum Lyman

Locality.—*Atlantis* station 15; mid-Atlantic west of Gibraltar (lat. 35° 37′ N., long. 30° 51′ W.); 3,200 meters; August 16, 1947. Two specimens.

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PROCEEDINGS OF THE ACADEMY

414th MEETING OF BOARD OF MANAGERS

The 414th meeting of the Board of Managers, held in the Cosmos Club, January 12, 1948, was called to order at 8:05 P.M. by the President, Dr. WALDO L. SCHMITT. Others present were: H. S. RAPPLEYE, N. R. SMITH, H. A. REHDER, M. A. MCCALL, H. B. COLLINS, JR., J. S. WADE, A. WETMORE, W. W. RUBEY, L. E. YOCUM, W. A. DAYTON, C. A. BETTS, A. O. FOSTER, C. L. GAZIN, and, by invitation, G. P. WALTON, J. I. HOFFMAN, E. A. CHAPIN, and A. T. MCPHERSON.

The Chairman of the Committee on Monographs, Dr. E. A. CHAPIN, announced that estimates had been obtained from several printers for the publication of Dr. HERBERT FRIEDMANN'S monograph *The Parasitic Birds of Africa*. These ranged from about $1,500 to $2,500 for 1,000 paper-bound copies. Buckram binding increased the estimates $450 to $460. From the record of the sale of Dr. Friedmann's earlier monograph of the cowbirds, Dr. Chapin considered that the present volume, published possibly as a supplement to the JOURNAL, would in all probability pay its way and recommended that the Academy accept it. The monograph was referred to the Board of Editors for further review and recommendations.

Ten persons were elected to membership.

The Chairman of the Committee on Science Legislation, Dr. A. T. MCPHERSON, briefly summarized current activity in science legislation, on which he would report more fully at the annual meeting. His talk was concerned principally with the progress of the Foreign Scholarships program and on H. R. 3342. Dr. McPherson proposed that serious consideration be given to the formation of a study group on science legislation. By an informal showing of hands the outgoing Board recommended to the incoming Board that a Science Legislation Committee or Study Group be reappointed for the coming year.

The Acting Chairman of the Committee on Academy Awards for Scientific Achievement in 1947, Dr. HENRY B. COLLINS, JR., presented the following recommendations for the three subcommittees:

Biological Sciences: None.

Engineering Sciences: HARRY WARREN WELLS, of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, in recognition of his distinguished upper-air research and organization of a world-wide network of ionospheric stations.

Physical Sciences: Dr. ROBERT D. HUNTOON, of the National Bureau of Standards, in recognition of his distinguished service in the advancement of electronics and its applications to other sciences and to modern ordnance.

The Board accepted the recommendations, but during the discussion it developed that there existed some misunderstanding as to the age limit of award winners. The Board voted that for future purposes the nominee for the award must not have passed his 40th birthday during the year for which the award was made.

The Chairman of the Committee on the JOURNAL and its Improvement, Dr. R. J. SEEGER, reported as follows:

The Committee has had several meetings, including those of special subcommittees, over a period of almost a year. During this time it has reviewed the reports of similar previous committees; it has also consulted with various past Editors of the JOURNAL and with the George Banta Publishing Co. After considering many aspects the Committee unanimously makes the following recommendations pertaining to the JOURNAL and its improvement:

(1) That an index of the JOURNAL be prepared and published for the first 40 volumes and for each succeeding 10 volumes.

(2) That the address of the Retiring President of the Academy be published without charge, including the first 50 reprints with covers.

(3) That each author be allowed, without charge, the equivalent of the first 50 four-page reprints without covers.

(4) That each invited Academy speaker whose address is published in the JOURNAL be allowed, without charge, the first 50 reprints without covers.

(5) That the size of the JOURNAL be increased to approximately 500 pages per year and that the JOURNAL be published economically in issues of 32 or 48 pages—say, 6 issues of each size.

(6) That in each issue one page (the Editorial Page) be allotted to the President of the Academy for his own use or designation.

(7) That the list of officers and committees (standing and special) of the Academy be

published on the third cover page (inside back) of each issue of the JOURNAL.

(8) That Editors of the JOURNAL be continuously vigilant in seeking papers of general interest, in securing copies of outstanding Academy addresses (footnote reference to occasion of delivery), and in selecting papers from different fields for any particular issue.

(9) That the Board of Managers authorize the appointment of a committee to study the functions of the Academy and to formulate a program that will integrate these functions, including the JOURNAL.

The Board voted that the recommendations of the JOURNAL Committee be brought up at the next meeting of the Board.

The Secretary, Dr. C. L. GAZIN, announced the death of Maj. Gen. GEORGES PERRIER, honorary member, formerly of Paris, France, on February 16, 1946; HARDEE CHAMBLISS, formerly of Catholic University of America, on June 1, 1947; and ROBERT H. LOMBARD, formerly of the Norton Company, Research Laboratories, Worcester, Mass., on October 11, 1947.

Dr. HARVEY I. CURTIS was transferred to the list of retired members, effective December 31, 1946.

The following letter to the Secretary from Dr. P. W. BRIDGMAN was read to the Board:

It is a great pleasure to learn that I have been transferred from regular membership to honorary membership in the Washington Academy of Sciences. Will you please express my appreciation to the Board of Managers.

The Treasurer, H. S. RAPPLEYE, announced that the auditing committee had met that morning, examined his books and the Academy securities, and gave him a "clean bill of health." He announced also that the transfer of investment certificates to an account book form in the First Federal Savings and Loan Association, as authorized at the 413th meeting, had been made.

The President, Dr. W. L. SCHMITT, stated that expenses of the Meetings Committee had exceeded the amount of the budget for this purpose and that in order to secure outstanding speakers he had paid out $100.30 more than allowed. It was his hope that, at the close of the Academy Year 1947, the unexpended amounts from the budgets of other offices and committees might be transferred to that of the Meetings Committee, up to the amount of $100.30, but without increasing the budget for the year. The Board authorized that Dr. Schmitt be so reimbursed for the expenditures made by him on behalf of the Meetings Committee.

The meeting was adjourned at 9:45 P.M.

C. L. GAZIN, *Secretary*